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Two different techniques are required to cover the resistivity spectrum pertinent to semiconductor devices. One technique measures the change in the transmission through a High-Q cavity loaded with the semiconductor material, while the other measures the microwave loss through thin sheets of the material when inserted into a waveguide. These techniques provide a means for measuring resistivities from .001 to 100 ohm - centimeters.

A MICROWAVE METHOD FOR MEASURING RESISTIVITY OF SEMICONDUCTORS

by

James Roger Seifert

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Professor in Charge

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1. INTRODUCTION

A new method for measuring resistivity of semiconductors has been developed using microwave frequencies instead of the conventional dc or low frequency ac techniques. This method is suitable in determining the bulk or sheet resistivity of semiconductor materials. The range of resistivities for semiconductors such as transistors, diodes, and solar cells is quite large, extending from 0.002 ohm-cm to over 100 ohm-cm. To cover this range by the microwave method it was found necessary to employ different techniques for different portions of the resistivity range. The techniques will be defined and compared.

In the normal production of material for transistors and diodes, the raw materials (silicon and germanium oxides) are refined and doped to the desired impurity level. They are formed into ingots about 1 inch in diameter and three or more inches long. These ingots are then sliced into one inch diameter discs, of thicknesses ranging from 0.006 to 0.040 inches. The resistivity (determined by the doping) varies along the length of the ingot. Electrical measurements are made to determine the sections having the desired resistivity range. Resistivity also varies across the cross section of the ingot. When slices are cut from the ingot, resistivity varies from the center of the slice to the edge of the slice.

To select material which has the proper resistivity for a contemplated device, therefore, it is necessary to make resistivity measurements accurately over small areas of the ingots and slices. The most widely used method is the four-point probe technique, but this has certain limitations. The usefulness of the microwave method lies in the fact that it eliminates most of these limitations.

2. CONVENTIONAL RESISTIVITY MEASUREMENT METHODS

The basic methods for measuring resistivity were derived directly from the method inherent in its definition. Resistivity or specific resistance, is defined as the resistance of a unit cube of material, as measured between any two opposite sides. By definition, test potentials are applied to the entire surfaces of the opposing sides. If the cube has sides of one centimeter, resistivity is in the conventional units of ohm-centimeters. However, semi-conductor materials require special techniques to provide ohmic contacts.

2.1 Two-Point Probe Method

A two probe method applies where the cross-sectional area of the material can be determined accurately. In this method (Figure 1) contacts are made to the ends of a bar or ingot (by plating or soldering) for the purpose of carrying the current. Voltage measurements are made with two probes which are accurately spaced and whose points contact the surface of the ingot. Resistivity can be calculated by:

$$\rho = \frac{VA}{IS} \qquad (1)$$

where ρ = resistivity in ohm-cm

V = voltage between the two probes

A = cross-sectional area in square centimeters

I = current flowing through the rod in amperes

S = spacing between the probes in centimeters

2.2 Four-Point Probe Method

Where the cross-sectional area cannot be calculated readily the four-point probe (Figure 2) is more effective. Usually the four points are equally spaced. The current flows through the two outer points and the voltage is measured between the two inner points. The pertinent relation is:[1]

$$\rho = \frac{V}{I}\left[\frac{2\pi}{\frac{1}{S_1}+\frac{1}{S_3}-\frac{1}{(S_1+S_2)}-\frac{1}{(S_3+S_2)}}\right] \qquad (2)$$

which reduces to

$$\rho = \frac{V}{I}2\pi S \qquad (3)$$

when the spacings between probes are equal.

However, relation (2) assumes that no reflecting boundaries are close to the probes, a condition which is not applicable to wafers or dice. Accounting for the various locations of boundaries with respect to the four-point probe and for both non-conducting and conducting types of boundaries requires a number of modifications to the basic formula. In the case where the thickness determines the nearest boundary, the material is very thin, and the distant side is non-conducting, the resistivity is given as follows:[2]

$$\rho = \frac{VW}{I}\frac{\pi}{\ln 2}F\left(\frac{W}{S}\right) \qquad (4)$$

1 L. B. VALDES. "Resistivity Measurements on Germanium for Transistors," Proceedings of the I.R.E., Vol. 42, pp. 420 - 427 (February 1954)

2 F. M. SMITS. "Measurement of Sheet Resistivity with the Four-Point Probe, The Bell System Technical Journal, Vol. XXXVII, pp. 711-718 (May 1958).

where V = voltage across the probes

I = current through the outer probes in amps.

W = thickness in centimeters

S = point spacing in centimeters

$F\left(\frac{W}{S}\right)$ = correction factor for thickness as follows:

$\frac{W}{S}$	$F\left(\frac{W}{S}\right)$
0.4	.9995
0.5	.9974
.5555	.99948
.6250	.9898
.7143	.9798
.8333	.9600
1.0	.9214
1.4286	.7938
2.0	.6336

2.3 Van der Pauw Method

Another method which has been used is the Van der Pauw technique.[3] Four points or contacts are made on the perimeter of the dice or wafer to be measured (Figure 3) and a dc current is passed between two alternate contacts, AB. The voltage between the two other contacts, CD is accurately

[3] Van der Pauw, L. J., "A Method of Measuring Specific Resistivity and Hall Effect of Discs of Arbitrary Charge - Phillips Research Reports, Vol. 13, 1958

measured and the resistance, or V/I ratio, is determined. The current is then passed through one of the same current contacts and an alternate contact (AD) and the voltage is measured across the two remaining contacts (BC). The resistivity is then determined by means of the following formula:

$$\rho = \frac{\pi d}{\ln 2} \frac{R_1 + R_2}{2} f\left(\frac{R_1}{R_2}\right) \quad (5)$$

where $R_1 = \frac{V_{CD}}{I_{AB}}$

$R_2 = \frac{V_{BC}}{I_{AD}}$

$f\left(\frac{R_1}{R_2}\right)$ = correction factor (plotted as a function of $\frac{R_1}{R_2}$ in ref. 3.)

If $R_1 \leq 1.5\, R_2$, then $f\left(\frac{R_1}{R_2}\right) \approx 1$ and no correction factor is needed.

If the contacts are symmetrically placed, i.e. on major and minor axis, then R_1 and R_2 and $f\left(\frac{R_1}{R_2}\right) = 1$

This method provides a means of measuring resistivity of very small dice -a result which would not be possible with the four-point probe because of the restriction of point spacing and close proximity to the edge.

2.4 Limitations of Conventional Methods

Nevertheless, of the three methods mentioned, the four-point probe method has been used most extensively. However, this method is subject to several limitations. Except when working with ingots, it requires that the thickness of the material be measured, and this is a source of possible error. Another disadvantage is that the sharp points of the probe can damage the semiconductor material, especially when they are dragged along a bar in making profile measurements. Also, the probes can be bent or damaged fairly easily, changing the point spacing and producing an error. The first limitation, the necessity of knowing thickness, was the stimulus for investigating a microwave technique to measure resistivity.

2.5 Depth of Penetration Considerations

Most materials used for semiconductor devices are initially cut into discs which are about 1 inch in diameter and from .006 to .040 inches thick. However, if electrical measurements could be confined to very small depths in the material then thickness measurements can be eliminated. The depth to which microwave signals are effectively confined is called the skin depth of depth of penetration. This is the depth at which the signal has been attenuated to 1/e or approximately 37% of its original value. The depth of penetration is calculated for three frequencies (9 Gc, 22 Gc, and 60 Gc) for various resistivity values (see Appendix A) by means of the following formula:[4]

$$\delta = \frac{1}{2\pi f \sqrt{\frac{\mu\epsilon}{2}\left(\sqrt{1+\frac{1}{(2\pi f)^2\epsilon^2\rho^2}} - 1\right)}} \qquad (6)$$

where δ = skin depth in meters

f = frequency in cycles per second

μ = permeability in henry/meter

ϵ = dielectric constant in farad/meter

[4] EDWARD C. JORDAN, "Electromagnetic Waves and Radiating Systems," Prentice Hall N.Y., P. 132

ρ = resistivity in ohm-meters

The results are plotted in Figure 4. The plot shows that there are a substantial number of thickness and resistivity combinations in the range of useful material where thickness exceeds depth of penetration. For example, the calculations at 22 Gc indicate that for slices 0.007 inch thick, thickness would exceed depth of penetration with resistivities less than 0.3 ohm cm. For 0.018 inch thick slices at the same frequency, this applies to resistivities less than 1.2 ohm-cm. A microwave approach could, therefore, be assumed to have reasonable potential for eliminating thickness measurements.

3. MICROWAVE RESISTIVITY MEASUREMENT METHODS

3.1 Reflection Method

The first method investigated dealt with the measurement of VSWR or return loss in a waveguide transmission line terminated by the semiconductor to be measured. An extremely low-resistivity material will reflect all the signal power applied to it. The return loss will then be zero decibels. Material of higher resistivities will both absorb and transmit more power and, therefore, reflect less. The return loss will increase progressively until the point of perfect impedance match between the sample and the waveguide system is obtained. At this point return loss will be infinite. Between these limits the resistivity versus return loss may be plotted as in Figure 5. It is understood that the area of the test sample used, if larger than desired, can be reduced by means of a tapered section or by masking off part of the sample with a brass aperture.

3.11 Circuit Description

The schematic diagram for the reflection method is shown in Figure 6. This method was tested at 9 Gc using waveguide with inside dimensions of 0.400 x 0.900 inch. The sample to be tested was placed across the open end of the transmission line, exposing an area of 0.400 inch x 0.900 inch. In this measurement the depth to which the material is being tested is δ, the depth of penetration. It follows that the material should be thicker than the depth of penetration, otherwise a portion of the incident signal will be radiated into the surroundings through the sample, causing reflections. The 9 Gc signal is generated by a klystron with a repeller modulated by a

60 cps signal. A wave meter is placed in the waveguide line to determine the exact operating frequency. Attenuators 1 and 3 (Figure 6) are used to adjust the signal level while attenuator 2 is a calibrated precision attenuator adjusted for every sample. The directional couplers shown in Figure 6 refer the incident and reflected signals in the main waveguide line to the crystal detectors in the secondary lines. The potentiometers across the detectors are used to adjust the signals to make up for differences in signal level. The incident and reflected signals are switched by a 30 cps electronic switching system and are alternately displayed on an oscilloscope.

3.12 Measurement Procedure

The test is made by initially calibrating the system with a perfect conductor placed over the test position producing 100% reflection of the incident signal and proceeding as follows: Attenuator 2 is set for some value which is higher than the expected return loss of the sample. Attenuators 1 and 3 are then adjusted to set the signal level at a desired value and the balance pots are adjusted for equal traces on the oscilloscope. The perfect conductor is then replaced with the sample to be tested and attenuator 2 is reset for equal traces. The difference in attenuation between these two conditions is then the return loss of the sample.

3.13 Results

A group of samples with known resistivities was measured and the results plotted in Figure 5. It is observed that the return loss varied only 3-3/4 DB for the resistivity range from .01 to 100 ohm-cm., thereby requiring very precise microwave measurements. Another disadvantage of this method is that the sample size must be large (in comparison to the four point probe).

A similar measurement was made for an identical microwave circuit at 22 Gc with a test aperture of 0.170 x 0.420. A plot of resistivity versus return loss for samples of known resistivity is shown in Figure 7. It is seen that the spread of return loss is now 6-1/2 DB for a resistivity range varying from .01 to 100 ohm-cm., or nearly twice that of the 9 Gc case. This is accounted partly by the fact that the depth of penetration into the material is less at the higher frequency and partly to the fact that the characteristic impedance of the line is different - which suggests that the value of resistivity for which perfect impedance match is obtained is different.

3.2 <u>High Q Cavity Method</u>

3.21 <u>Circuit Description - 9 Gc</u>

In the pursuit of methods yielding greater return loss spread, a high Q resonant cavity was employed to lightly couple a generator to a crystal load as illustrated in Figure 8. The signal transferred between these two elements increases with the Q of the coupling cavity. The value of Q is made to vary by using the specimen to form a portion of the cavity wall. Differences are measured between the transmitted signal level when the cavity opening is filled with a good conductor (such as gold plated brass) and when the opening contains the test sample. The cavity employed was a section of waveguide $\lambda g/2$ units long when operating in the TE_{10}, mode with a side opening of 0.218 x 0.400 inches. The ends of this waveguide cavity contain a brass plate with a small coupling hole about 3/16 of an inch in diameter (See Figure 9). An isolator is placed between the attenuator and the detector so that mismatches due to the detector mount will not affect the accuracy of the attenuator. With this circuit the signal incident to the cavity and the signal transmitted through it are detected oscilloscopically by means of the electronic switch.

3.22 Measurement Procedure

The measurement procedure is as follows: The material to be tested is placed over the opening in the cavity and attenuator 1 (Figure 8) is set to zero. The frequency of the microwave generator is adjusted to the resonant frequency of the cavity (maximum signal); the incident and transmitted signal are then made equal by means of the balancing potentiometers. A piece of gold plated brass is now placed over the cavity opening and attenuator 1 is re-adjusted for equal signal levels. The attenuator reading then gives the loss in db produced by loading the cavity with the semiconductor material.

3.23 Results - 9 Gc

A group of samples of known resistivities was measured and a plot of resistivity against cavity loss at 9 Gc was made (Figure 10). These specimens were ingots so that the thickness (t) greatly exceeded the depth of penetration ($t \gg \delta$). It is noted that the change in attenuation versus the change in resistivity is much greater than that obtained with the return loss method, thereby providing greater precision in readings.

To effect reliable measurements for specimens with thickness comparable to δ , it was found necessary to back the thin slices with a material of known resistivity. In this procedure gold plated brass was used for calibration. Another method attempted involved a semiconductor ingot of high resistivity, such as 100 ohm-cm. In each case the thickness as well as the resistivity is a factor in determining the cavity loss so that, unfortunately, for these cases, as in the four point probe technique the thickness must be accurately known. Figure 11 shows a plot of resistivity vs. cavity loss for slices backed with gold plated brass and with 100 ohm-cm material. The use of brass as a backing material was found not very effective because of the narrow spread and consequent ambiguity of the results. The heavy line represents thick slices and ingots. A family of curves for different thickness was plotted using samples with known resistivity values. Figure 12 illustrates how the two methods of backing can be used to determine both resistivity and thickness. Vertical lines are drawn for the transmission change with brass backing and also with 100 ohm-cm backing. Figure 12 is then studied to determine at what horizontal level these two lines touch the same thickness curves. In this case, the transmission change with brass backing was measured to be 4.7 db, and with 100 ohm cm backing, 10.2 db. From Figure 12, it is determined that at the horizontal resistivity of 0.8 ohm cm, the same thickness of 0.012 inch is intersected by the vertical construction lines. The resistivity is then 0.8 ohm cm, and the thickness 0.012 inch.

3.24 Circuit Description - 22 Gc

In order to reduce the depth of penetration and also the surface area of the specimen a circuit similar to Figure 8 was assembled for operation at 22 Gc. At this frequency the sample area selected was 0.170 x 0.200 inches, which is comparable to the area tested with four-point probe techniques. This measurement area is small compared to the one inch diameter of slices. The selection of the size of the opening was a compromise of several factors. One was the desire for small size in order to obtain better resolution of resistivities with respect to distance. (The sample area, the area of the material actually involved in the measurement, is only slightly larger than the cavity opening.) Also favoring small openings was the observed increase in the slope of the calibration curve (at the higher frequencies) as the size of opening was increased. Of course, as this slope increases, changes in resistivity produce smaller changes in the transmission through the cavity and precision decreases. However, a lower limit in cavity opening size is determined by the lowest resistivity value to be measured because this resistivity must produce a measurable effect on cavity transmission.

Impedance match was obtained by using seven tuning screws, inserted in the transmission lines immediately before and after the high-Q cavity. Match is adjusted for the flattest transmission over the range under study. The curve of resistivity versus cavity loss at 22 Gc is shown in Figure 13 for thick slices (bulk), 0.007 inch thick slices and 0.018 inch thick slices.

3.25 Results - 22 Gc

In comparison with the curve at 9 Gc. it is observed that the slope is less steep at 22 Gc for the lower resistivity values, but approximately the same between 1.0 and 100 ohm-cm. The 22 Gc circuit is therefore more useful because it extends the measurable range in resistivity by a decade over the 9 Gc circuit and at the same time it utilizes a smaller specimen area. However, the precision of the high-Q cavity method becomes inadequate at the higher resistivities. The slope of the curve increases as resistivity increases. For the high-Q cavity method at 22,000 megacycles the practical limits of acceptable accuracy are: 1.0 ohm-cm for 0.007 inch thickness and 10.0 ohm-cm for 0.018 inch thickness.

3.3 Transmission Loss Method

In the High-Q cavity method, most of the microwave energy incident upon this slices of high resistivity penetrates through. Advantage is made of this in an effort to get a greater spread of attenuation vs. resistivity for high resistivity specimens.

3.31 High-Q Cavity Circuit (1)

The first method investigated employed the high-Q cavity circuit with the addition of a crystal detector and a ferrite isolator (See Figure 14). The signal power that penetrated the aperture and the specimen was detected by a crystal detector placed on top of the specimen and transmitted to the oscilloscope through the electronic switching system. This signal was compared oscilloscopically with the signal that passed directly through the cavity.

The traces were made equal by adjusting the precision waveguide attenuator. A different attenuator setting results for each resistivity, and a plot of attenuator reading vs. resistivity is shown in Figure 15.

It is observed that the spread between 0.5 and 5 ohm-centimeters for a 19 mil thickness is approximately 19.5 db. The spread over the same resistivity range for the high-Q cavity method is approximately 7.5 db. It is apparent that over the resistivity range where the signal penetrates the sample, greater accuracy can be obtained due to better resolution in reading the attenuator. Above 10 ohm-cm., however, there is little improvement.

A drawback of this method is that the two crystal detectors are not kept at the same levels as resistivity varies. No two crystals have exactly the same output at different microwave levels, and hence the accuracy of this method is reduced by an amount depending upon the variation of the crystals. Another disadvantage is that both signals change when the cavity is loaded with the specimen or when the frequency of the signal is changed.

3.32 High - Q Cavity Circuit (2)

To eliminate these problems another method was attempted. This method compared the signal through the aperture in the cavity with the signal incident to the cavity. The circuit for this method is very similar to the previous one as shown in Figure 16. The differences are: (1) the transmission line is now terminated and the signal which is used for a reference is detected by a crystal preceeding the cavity, (2) the attenuator is shifted to a position ahead of the cavity. The two detectors will now see the same power level at balance and the reference signal will not be affected by the loading of the cavity.

The results (plotted in Figure 17) indicate a smaller spread in attenuator reading over the same resistivity range compared to the previous method. A possible explanation for the difference is that the cavity influenced the readings of the first method and distorted the results.

3.33 Transmission Loss Circuit

The third method attempted consisted of putting a brass plate containing a small aperture over the end of the waveguide transmission line and eliminating the cavity. A diagram of this plate and waveguide assembly is shown in Figure 18. The slice to be tested is placed over the aperture and the crystal detector placed on top of it. The crystal then detects the signal which penetrates the sample. The circuit schematic is shown in Figure 19.

This is nearly equivalent to placing the sample in the waveguide line and measuring the loss in transmission due to the sample. The difference, of course, is that the sample is placed across an aperture only a small fraction of the total waveguide opening and effects due to the aperture must be taken into consideration.

The operation of this circuit is similar to the previous one. The crystal mount is placed directly over the aperture and the two traces are made equal on the oscilloscope with the attenuators set at some high value. As the samples of various resistivities are placed over the opening, the power transmitted to the crystal will diminish and attenuation will have to be taken out of the line to return to the same crystal level. The readings from the attenuator are then plotted against resistivity as shown in Figure 17, Method 3. Figure 20 shows a curve for the same circuit at 22 Gc with a rectangular orifice 0.170 x .200 inches.

3.34 Results

The transmission loss method is an improvement over the high-Q cavity method in providing accurate measurement at high resistivities and for offering better precision at all resistivities for which it is applicable. At the lower end of its resistivity range it offers a 14-decibel change in transmission loss per decade of resistivity (compared to 3 1/2 DB per decade with the high-Q cavity method) and an acceptable precision up to 60 ohm-cm. The upper limit of 60 ohm-cm is based on a loss of 0.60 db and a measuring accuracy of the instrumentation of about 0.03 or 0.04 db. Extension of the range of accurate measurement to higher resistivities can be accomplished by using instrumentation of greater precision.

3.4 Calibration Methods

In order for the readings from the microwave test equipment to be useful, a correlation between these readings and the resistivity of the specimen being tested must be obtained. The most obvious method is to use samples of known resistivity and plot readings from the waveguide attenuator versus resistivity. The standard method for determining resistivity is the four point probe, however, which makes the accuracy of the microwave techniques dependent upon the accuracy of the four point probe. Several methods have been developed to eliminate the need for four point probe readings.

3.41 Loss Per Inch

One of the methods employs the relationship of depth of penetration. It was stated previously that when a microwave signal penetrates a slice whose thickness equals its depth of penetration it loses 63% of its power. This is equivalent to a loss of 8.68 db. If the depth of penetration is calculated for a particular resistivity, the loss per .001 inch can be calculated for that resistivity. This was done (see Appendix A) and a plot of resistivity versus loss per .001" is shown in Figure 21.

This loss differs from the loss determined by the transmission loss microwave method, however. The transmission loss is the sum of three losses: the signal loss due to the impedance mismatch between the input waveguide and the slice, the transmission loss in the slice, and the signal loss due to the impedance mismatch between the slice and output waveguide. If the input and output mismatch losses can be determined and subtracted from the total transmission loss, the loss through the slice and, hence the resistivity can be found.

The mismatch losses can be calculated if the VSWR of the input and output impedance matches are known. Another method involves tuning out both mismatches by means of an adjustable tuner at the input and output of the test position. When the mismatches are tuned out, the transmission loss equals the loss through the slice and resistivity can be found using

Figure 21. The most accurate method is to measure the change in transmission loss of a slice as its thickness is changed. The thickness can be changed by breaking a slice in half and sandwiching the two halves together. Measurements are taken before and after breaking the slice. Another method involves measuring a slice, lapping it down by a few mils and remeasuring it. The change in loss per change in thickness will give the loss per .001" of the slice and its resistivity can be obtained from Figure 21.

These procedures are limited to resistivities and thicknesses which are measurable by the transmission loss technique. Thickness and resistivity must also be chosen to produce a loss through the slice large enough to prevent the input and output mismatches from changing after the slice is lapped.

The preceeding procedures are time consuming and destructive, but the results can be used to plot an accurate curve of resistivity versus total transmission loss which can be used for other slices. A curve can be plotted for one thickness, for example, and then using Figure 21, curves of any thickness can be drawn (because the change in loss per change in thickness is known). The result will be a family of curves for different thicknesses from which the resistivity of different size specimens can be obtained.

3.42 Sheet Resistivity

If the bulk resistivity in ohm-cm of a sample is divided by its thickness in cm., sheet resistivity is obtained in ohm/square. Sheet resistivity versus transmission loss is plotted in Figure 22 and was obtained from Figure 20 by dividing the resistivity by the thickness. It is observed from the curve that various thickness slices deviate from a single line at low resistivities where the slices are thicker than the depth of penetration. This is caused by the change in input and output mismatch losses which are dependent on volume resistivity and not sheet resistivity. The transmission loss is calculated as shown in appendix B for various resistivity. The calculated curve is shown dotted in Figure 23.

The calculated curve coincides well with the curve determined experimentally for thin slices. An adjusting factor is needed, however, for slices which are not thin compared to the depth of penetration.

4. CONCLUSION

The prime aim that originally stimulated the microwave approach, eliminating thickness measurements, has only been partially met. With the high-Q cavity method a sizable portion of the combinations of resistivity and thickness fall in the range where depth of penetration is smaller than thickness. For these combinations thickness measurements are not required. The overlap in the effective ranges of the high-Q cavity method and the transmission loss method permits the less precise high-Q cavity method to be used only where the advantage of eliminating thickness measurements applies; all other measurements can be made by the more precise transmission loss method, which requires slice thickness measurements. Of all the various techniques described these two provide the most accurate readings. Initially all the methods were tried at a frequency of 9 Gc, but it was found that a greater spread of attenuation versus resistivity was obtained at 22 Gc with the added advantages of smaller test area and less depth of penetration. It can be concluded that there would be an advantage to go to higher frequencies, say 60 Gc, if greater accuracy is desired.

The chief advantage of the two microwave methods of measuring resistivity over the 4-point probe method is the saving of time. Even allowing for measuring the thickness of the wafers, two resistivity measurements can be made in the time required to make one measurement by the four-point probe method. Another major advantage is improved accuracy and repeatability, once the microwave equipment has been calibrated. The microwave equipment is free from the possibility of mechanical misalignment and consequent errors. This is an improvement over the four-point probe's susceptibility to variation of point spacing.

Up to the present, the practical application of these methods has been limited to silicon, although experiments with germanium and knowledge of the properties of other materials indicate potential applicability to other materials. As new regions of resistivity and new materials assume importance, the microwave approach to resistivity measurements will undoubtedly be extended and improved.

APPENDIX A

1. DEPTH OF PENETRATION

By use of the following relation the depth of penetration for various resistivities and frequencies can be determined. A sample calculation is shown with a table of depth of penetration for various resistivities at three frequencies: 9 Gc, 22 Gc, and 60 Gc.

Let: $f = 22 \text{ Gc.}$ $\qquad \rho = 3 \text{ ohm-cm} = .03 \text{ ohm-m.}$

then $\omega = 2\pi f = 138 \times 10^9$ $\qquad \sigma = 33.3 \text{ mho/m}$

$\omega^2 = 1.9 \times 10^{22}$

$\mu = 4\pi \times 10^{-7} = 12.56 \times 10^{-7}$

$\epsilon^2 = 1.13 \times 10^{-20}$

$\omega^2\epsilon^2 = 215$

$$\delta = \frac{1}{138 \times 10^9 \sqrt{6.68 \times 10^{-17}\left(\sqrt{1 + \frac{1106}{215}} - 1\right)}} \qquad (1)$$

$$= \frac{1}{138 \times 10^9 \sqrt{6.68 \times 10^{-17}(1.48)}}$$

$$= \frac{1}{138 \times 10^9 (9.95 \times 10^{-9})}$$

$$= \frac{1}{1373}$$

$$\delta = 7.28 \times 10^{-4} \text{ m.}$$

$$= 7.28 \times 10^{-2} \text{ cm.}$$

$$= .02865 \text{ in.}$$

TABLE 1

DEPTH OF PENETRATION IN INCHES

	FREQUENCY		
ρ (ohm-cm)	9 Gc	22 Gc	60 Gc
.01	.00210	.00134	.00812
.03	.00362	.00232	.00141
.1	.0066	.00423	.00256
.3	.0115	.00734	.00445
1.0	.0210	.0134	.00982
3.0	.0394	.0287	.0232
10.0	.087	.0755	.0703
30.0	.223	.221	.218
100.0	.726	.725	.722

2. LOSS PER INCH

The loss per inch or one thousandth of an inch can be calculated by dividing 8.68 DB, the loss per depth of penetration, by the depth of penetration at a particular resistivity.

$$\text{Ex: Loss/inch} = \frac{8.68}{.00134} = 6480 \qquad (2)$$

$$\text{or} \quad \text{Loss/.001 inch} = 6.48 \text{ DB} \qquad (3)$$

A table was constructed of Loss/.001 inches vs. resistivity at 22 Gc and is shown below:

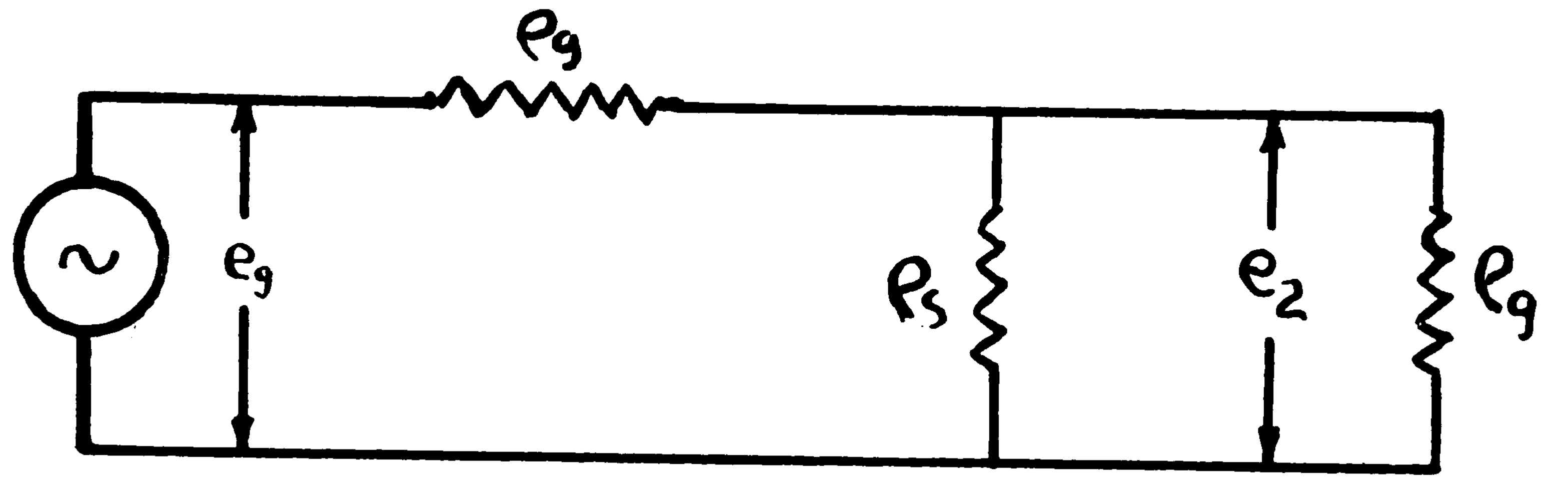
TABLE II

ρ (ohm-cm)	Depth of Penetration (in.)	Loss/.001" (DB)
.001	.00423	20.5
.01	.00134	6.48
.03	.00232	3.74
.1	.00423	2.05
.3	.00734	1.18
1	.0134	.648
3	.0287	.302
10	.0755	.115
30	.221	.0393
100	.725	.0120

APPENDIX B

CALCULATION OF TRANSMISSION LOSS

A mathematical analysis can be made of the transmission loss caused by a thin piece of material of resistivity ρ s placed across a waveguide transmission line using transmission line analogy. The transmission line equivalent circuit of the microwave network is shown below.



where: λo = wavelength in free space

λg = wavelength in the waveguide

ρg = impedance of waveguide = $\frac{\lambda_g}{\lambda_o}$ 377 ohms/sq.

ρs = sheet resistivity of slice being measured in ohms/sq.

The transmission loss on a voltage basis is as follows:

$$\text{Loss} = 20 \log_{10} \frac{e2'}{e_2}$$

where: e_2' = voltage at output with slice in fixture ($\rho = \rho s$)

e_2 = voltage at output with no slice in fixture ($\rho = \infty$)

$$e_2' = \frac{e_g}{\rho_g + \frac{\rho_g \rho_s}{\rho_g + \rho_s}} \times \frac{\rho_g \rho_s}{\rho_g + \rho_s} = \frac{e_g \rho_s}{\rho_g + 2\rho_s}$$

$$e_2' = \frac{e_g}{2 + \frac{\rho_g}{\rho_s}} \quad ; \quad \text{as } \rho_s \to \infty, \ \frac{\rho_g}{\rho_s} \to 0$$

$$e_2 = \frac{e_g}{2}$$

$$\text{Loss} = 20 \log_{10} \frac{e_2'}{e_2} = 20 \log_{10} \left[\frac{e_g \dfrac{\rho_s}{2\rho_s + \rho_g}}{e_g/2} \right]$$

$$\text{Loss} = 20 \log \frac{2\rho_s}{2\rho_s + \rho_g}$$

$$\text{Loss} = 20 \log \frac{1}{1 + \dfrac{\rho_g}{2\rho_s}}$$

at $f = 22$ kMc, $\dfrac{\lambda g}{\lambda 0} = 1.2996$

$$\rho g = 377 \times 1.2996$$
$$\rho g = 488 \text{ ohm/sq.}$$

From the equation for loss and the above value for ρg, the following table can be constructed:

ρs (ohms/square)	Transmission Loss (Db)
1000	1.9
400	4.2
100	10.7
40	17.0
20	22.4
10	28.1
4	35.9
1	47.8
0.1	67.8
0.01	87.8
0.001	107.8

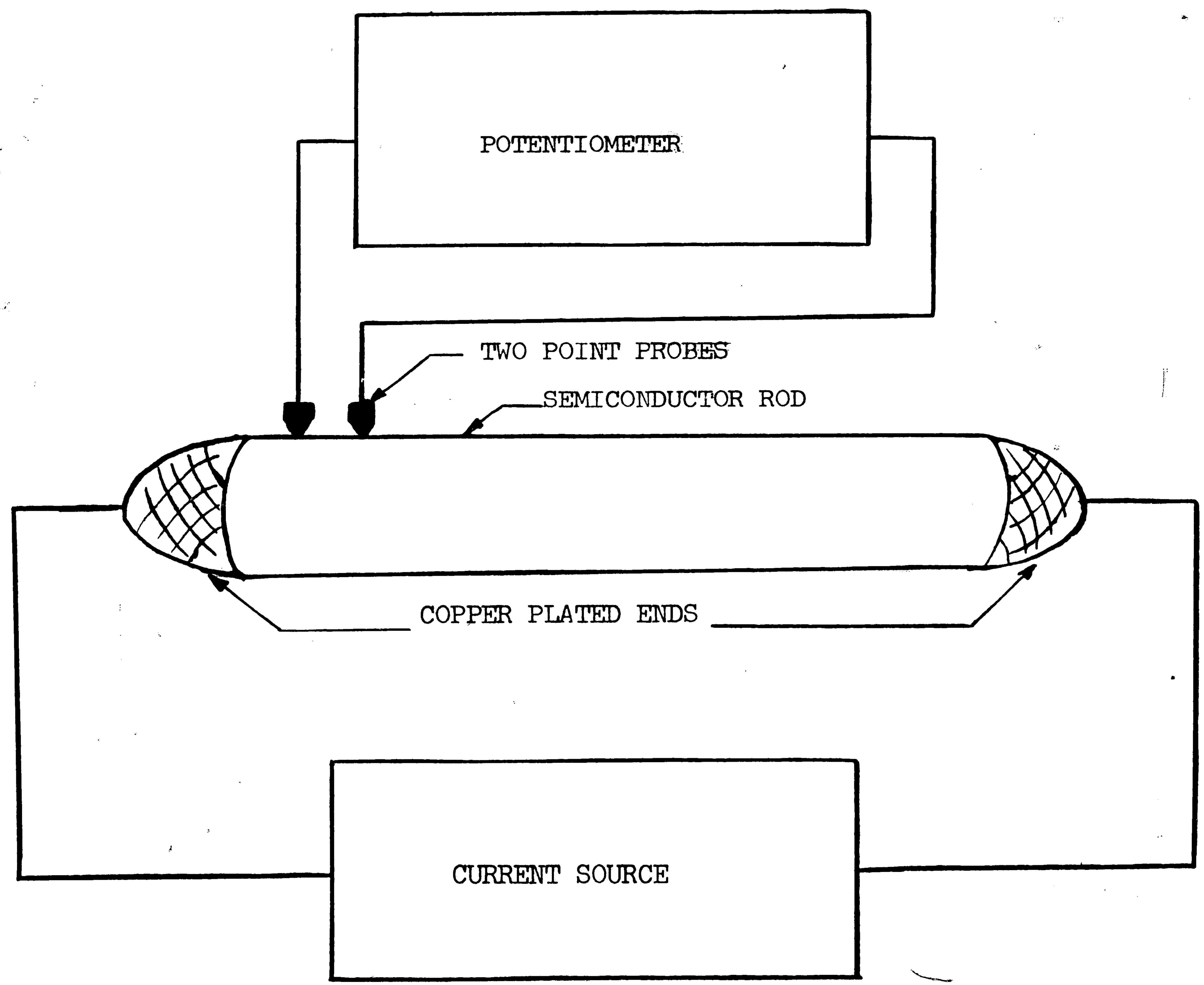


FIG. 1.

TWO POINT PROBE

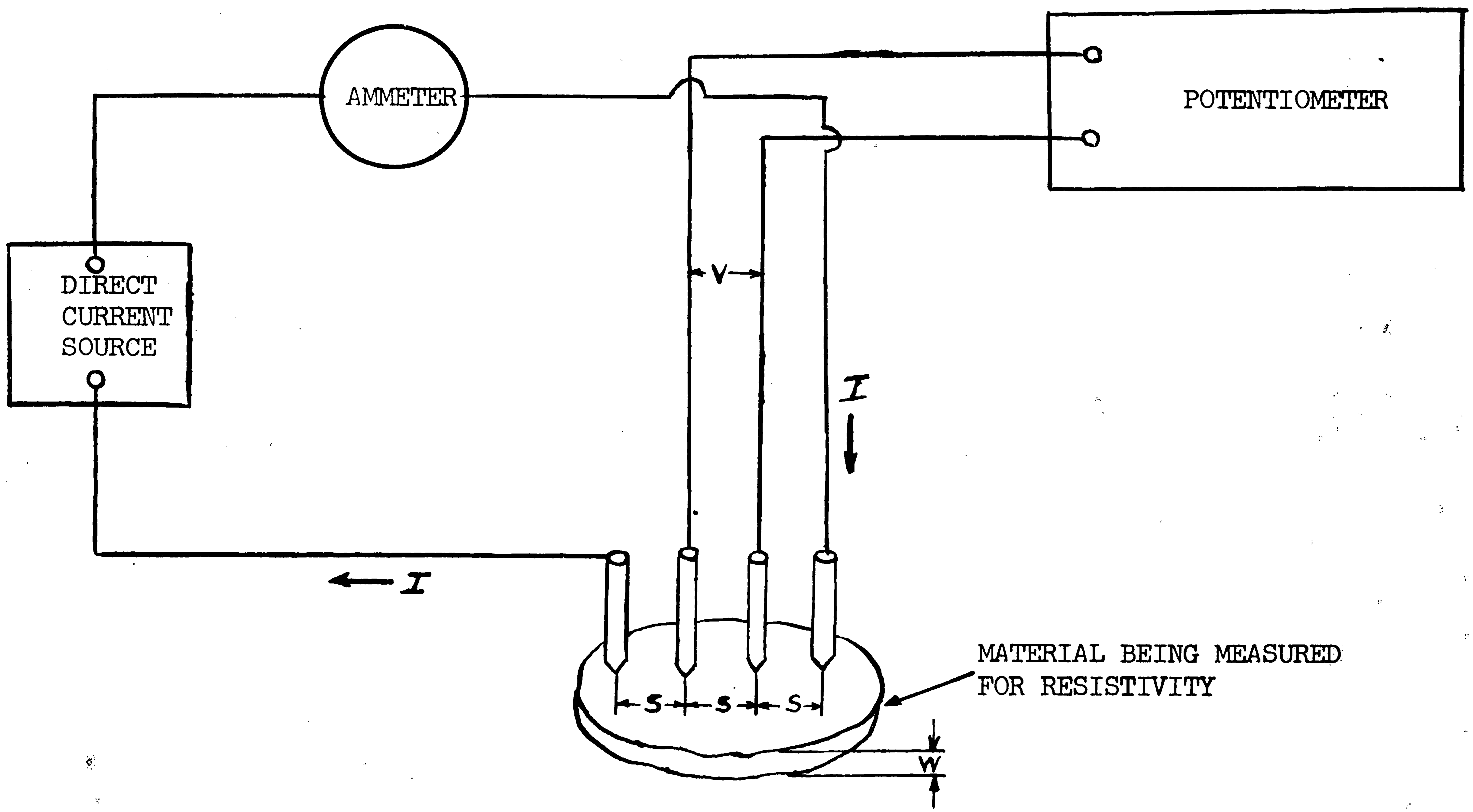


FIG. 2

FOUR POINT PROBE

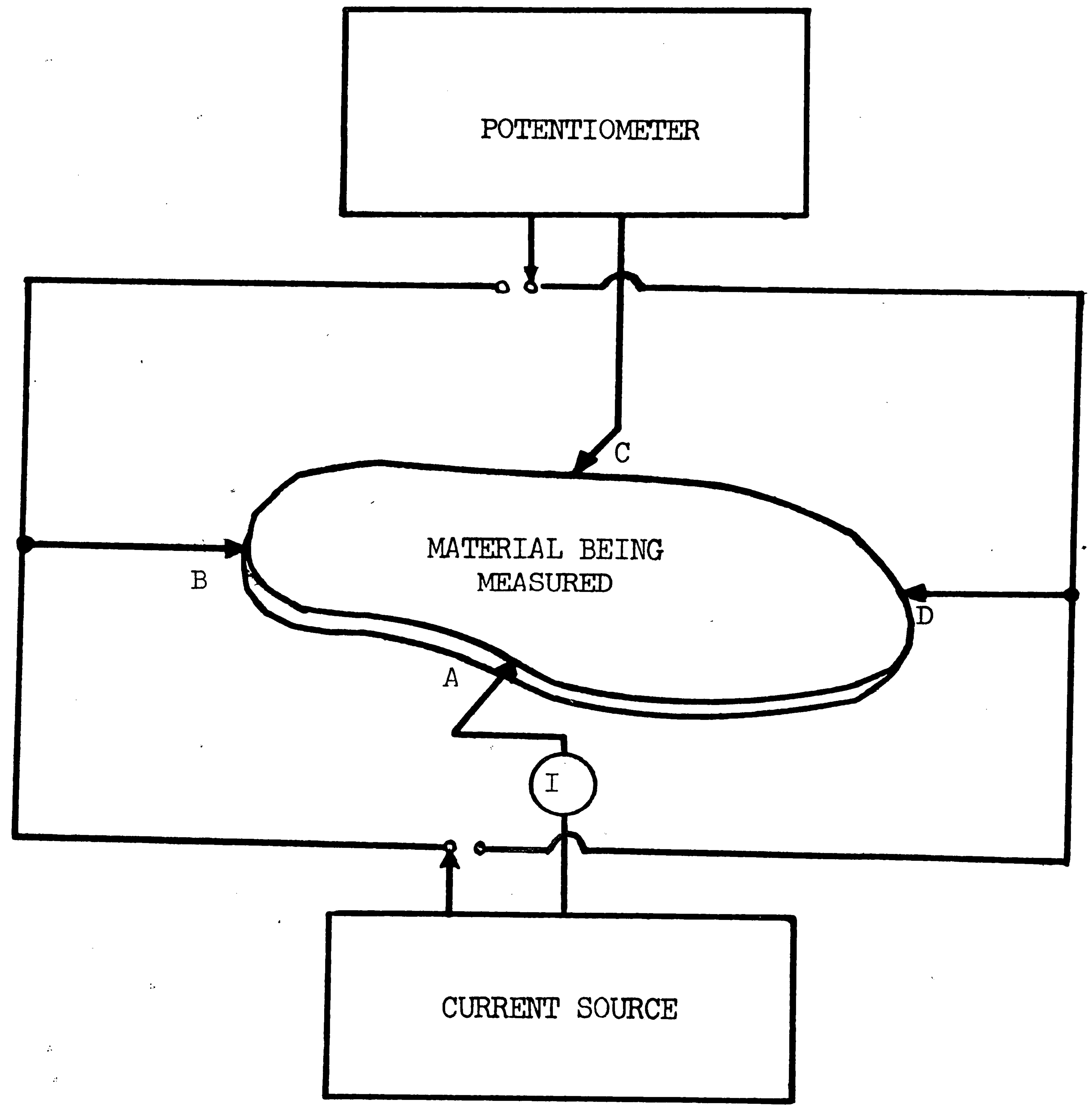


FIG. 3

van der PAUW PROBE

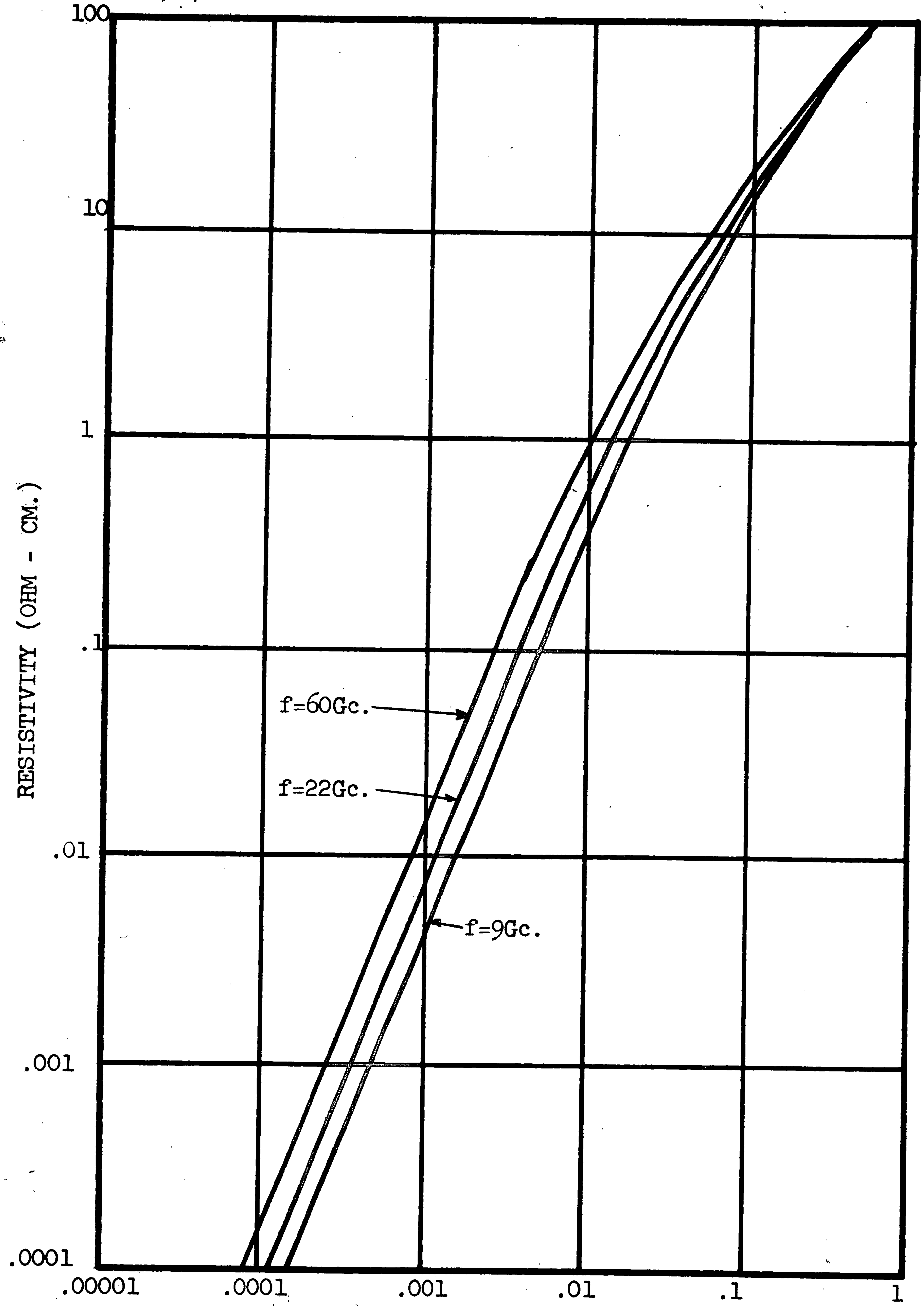


FIG. 4

DEPTH OF PENETRATION VS. RESISTIVITY

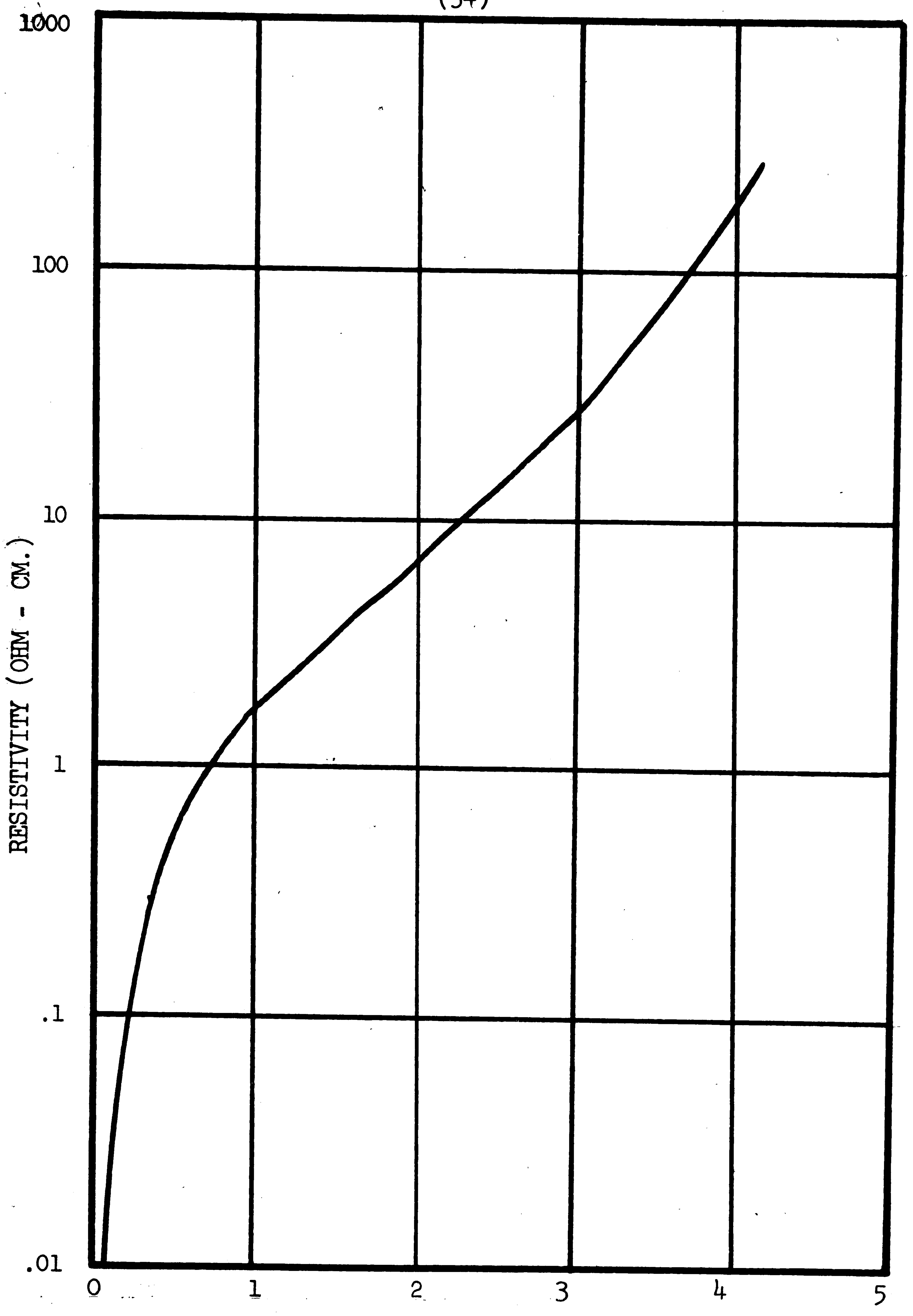


FIG. 5

RETURN LOSS VS. RESISTIVITY AT 9Gc.

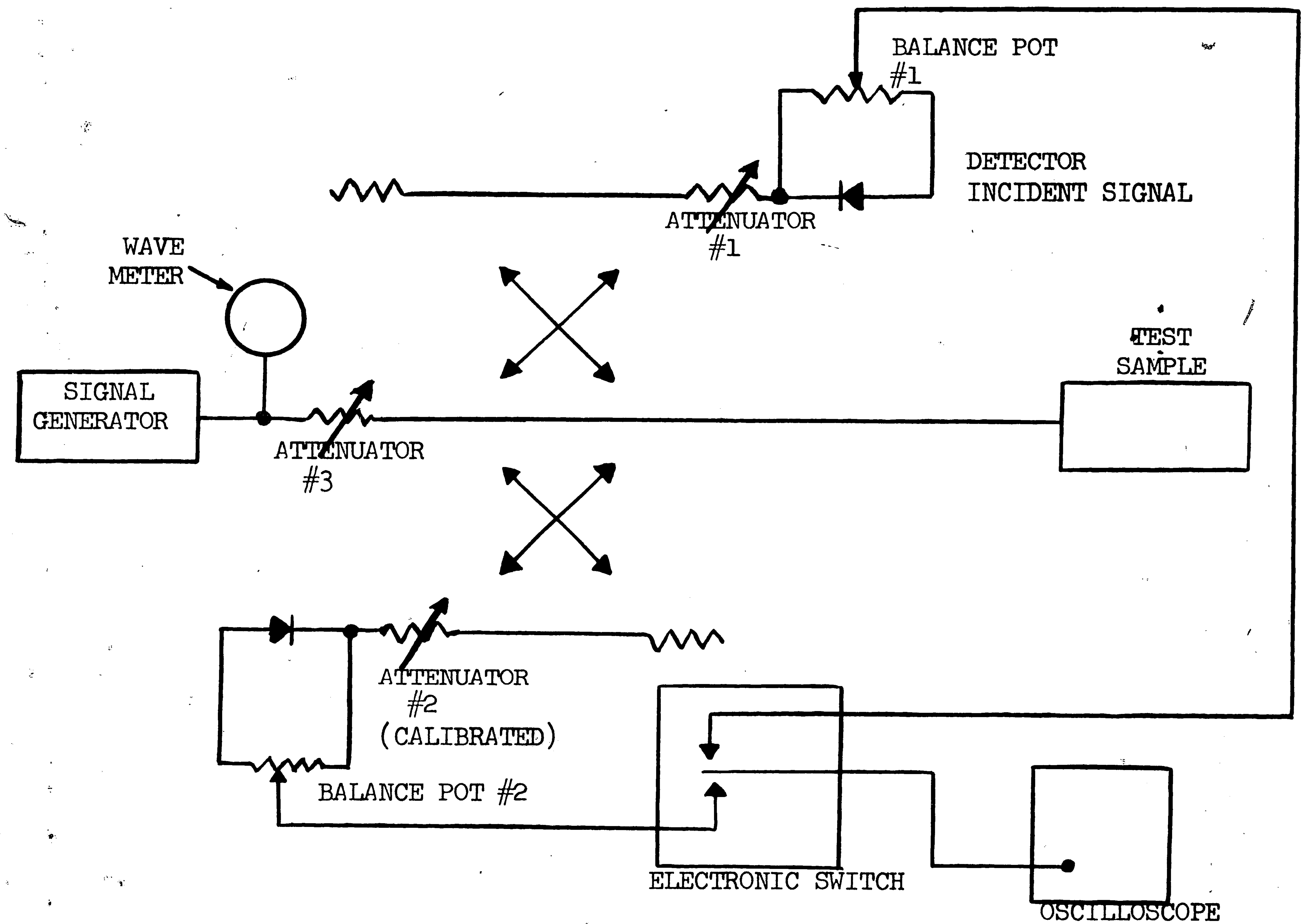


FIG. 6

RETURN LOSS CIRCUIT DIAGRAM

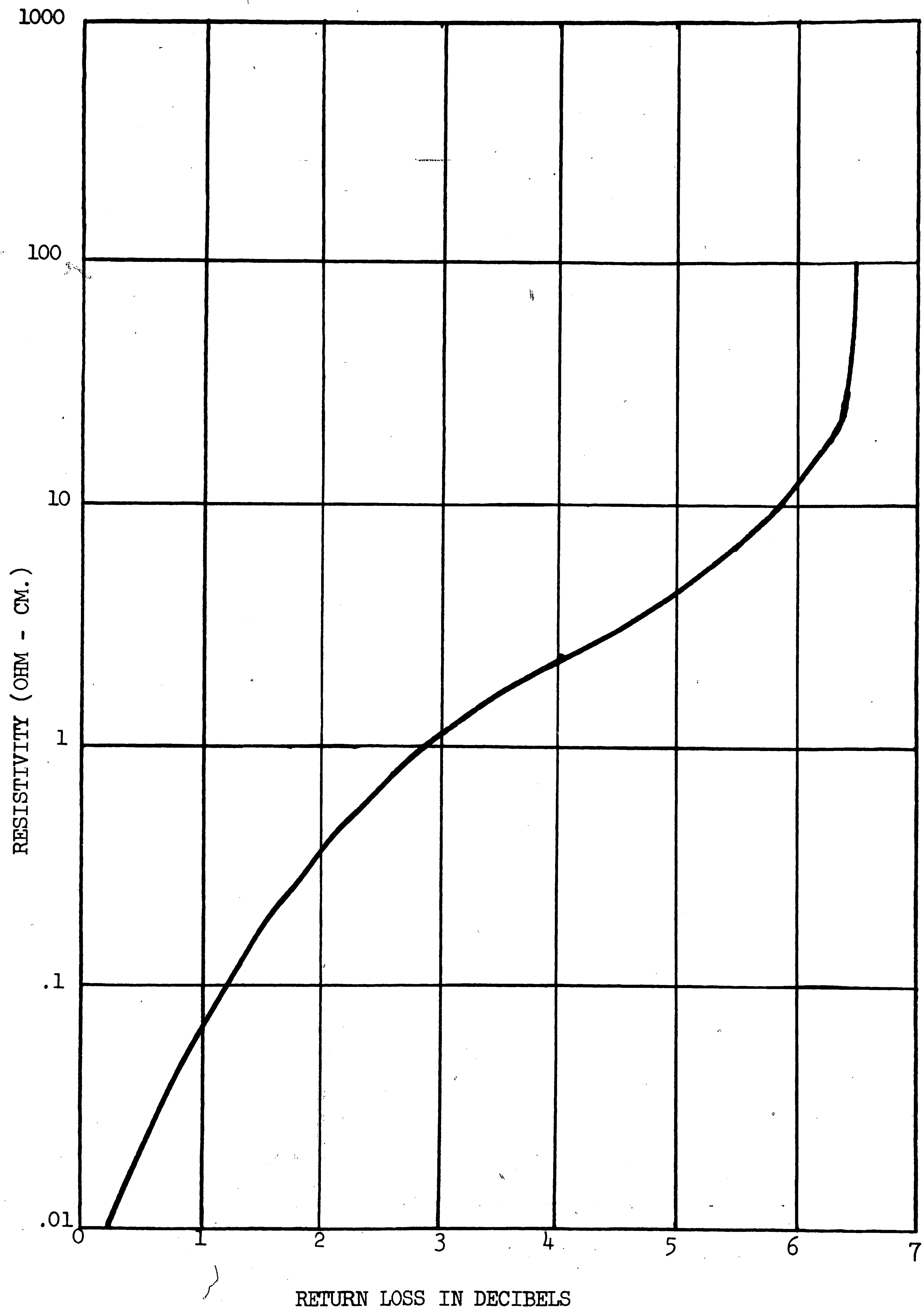


FIG. 7

RETURN LOSS VS. RESISTIVITY AT 22Gc.

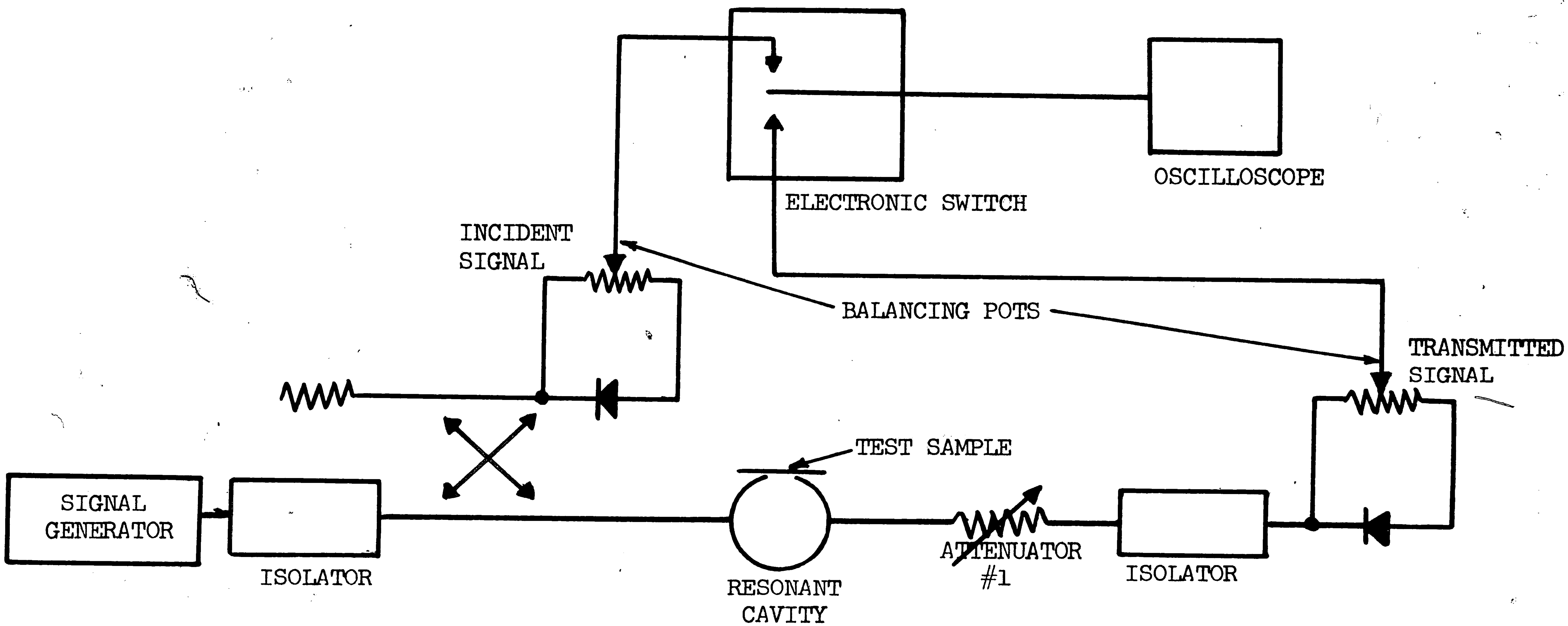


FIG. 8

HIGH-Q CAVITY CIRCUIT DIAGRAM

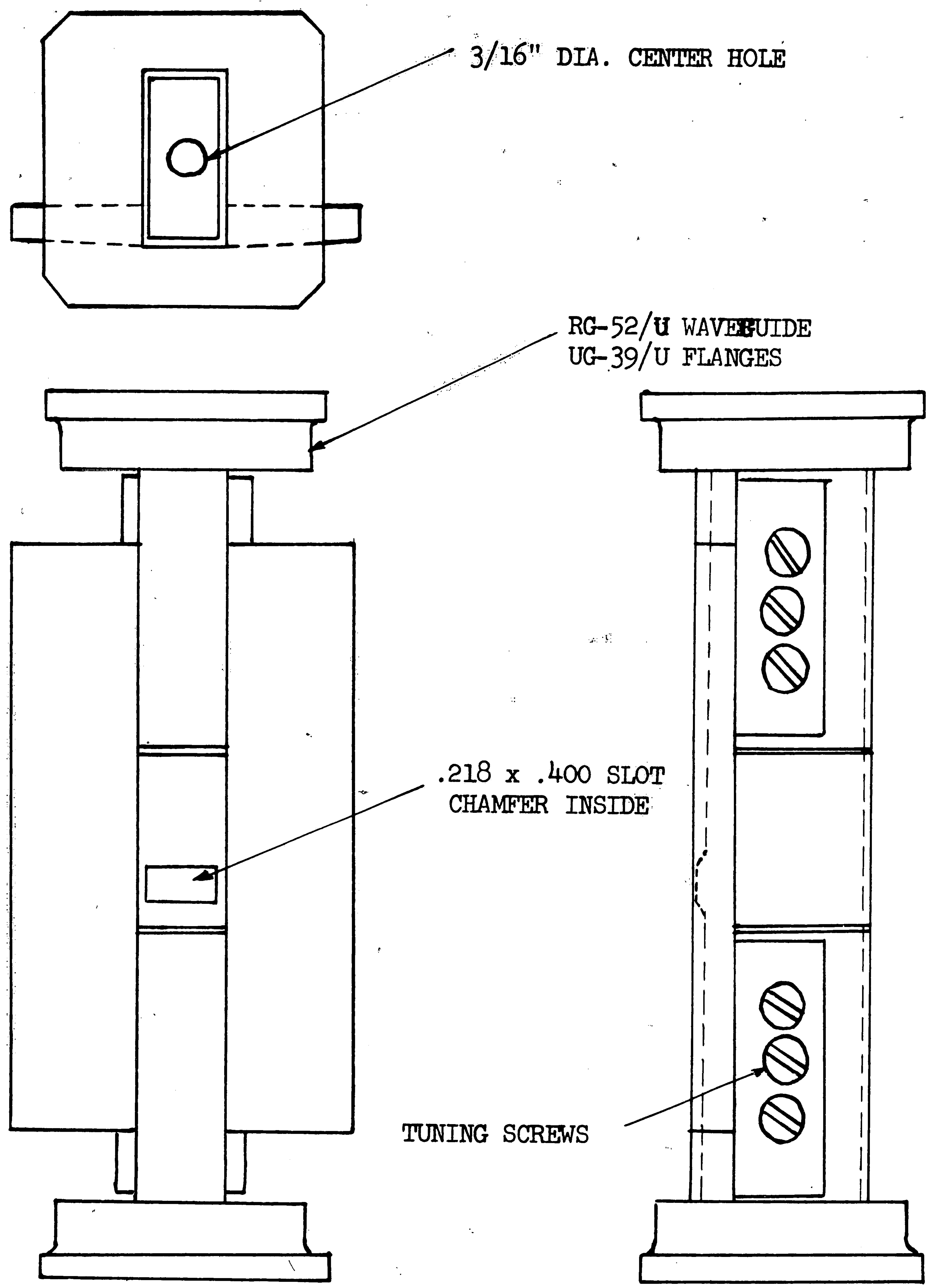


FIG. 9

HIGH-Q CAVITY

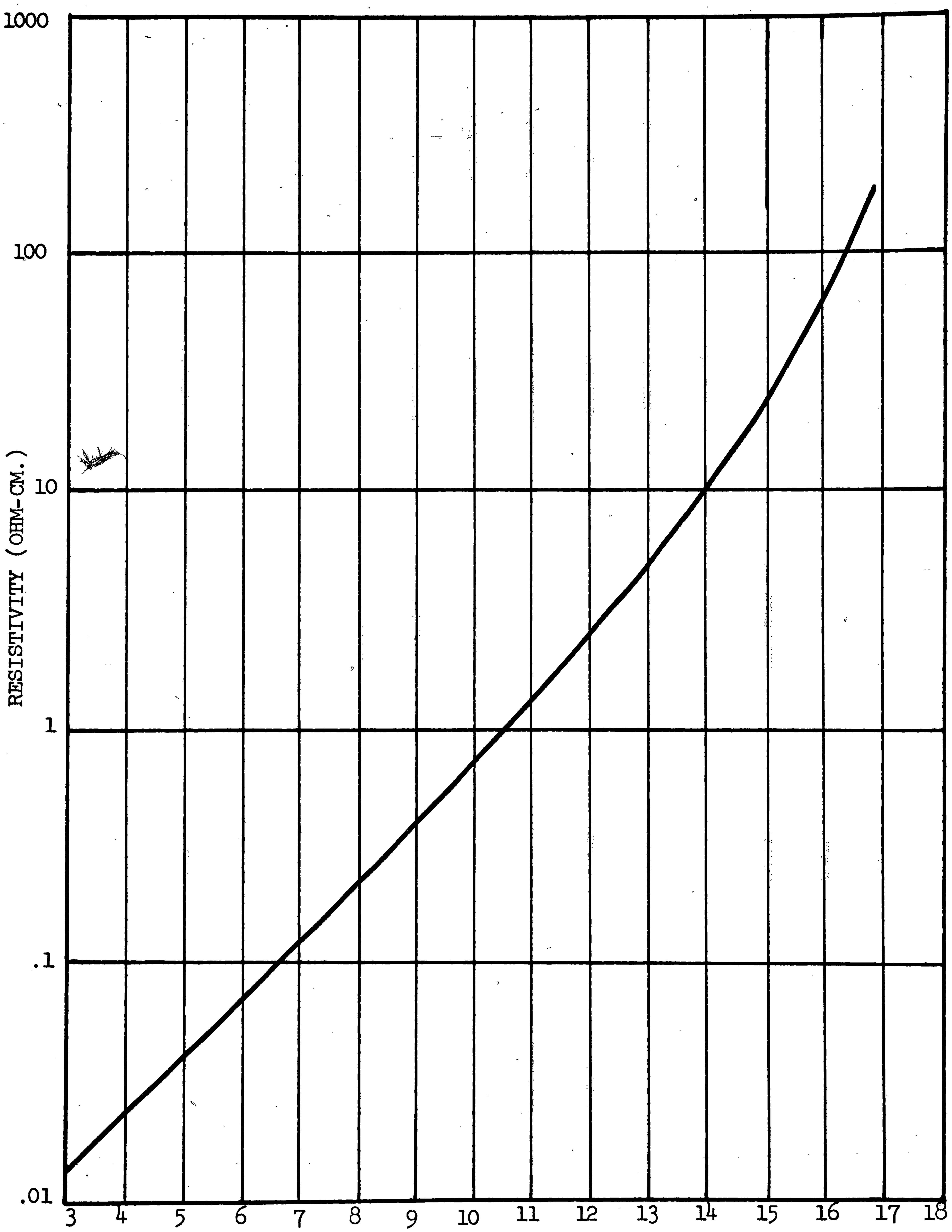


FIG. 10
CAVITY LOSS VS. RESISTIVITY AT 9Gc. (1)

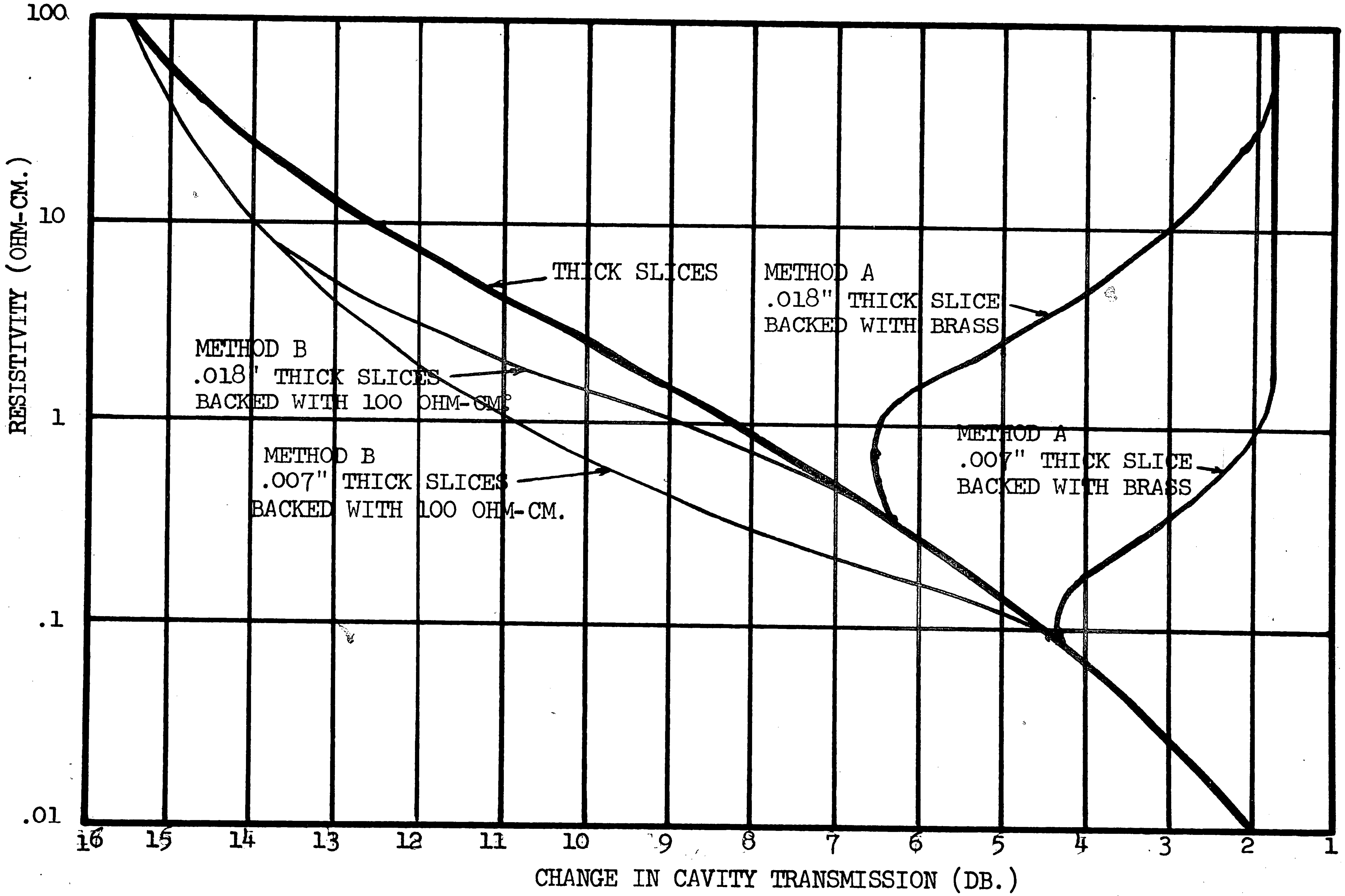


FIG. 11

CAVITY LOSS VS. RESISTIVITY AT 9Gc. (2)

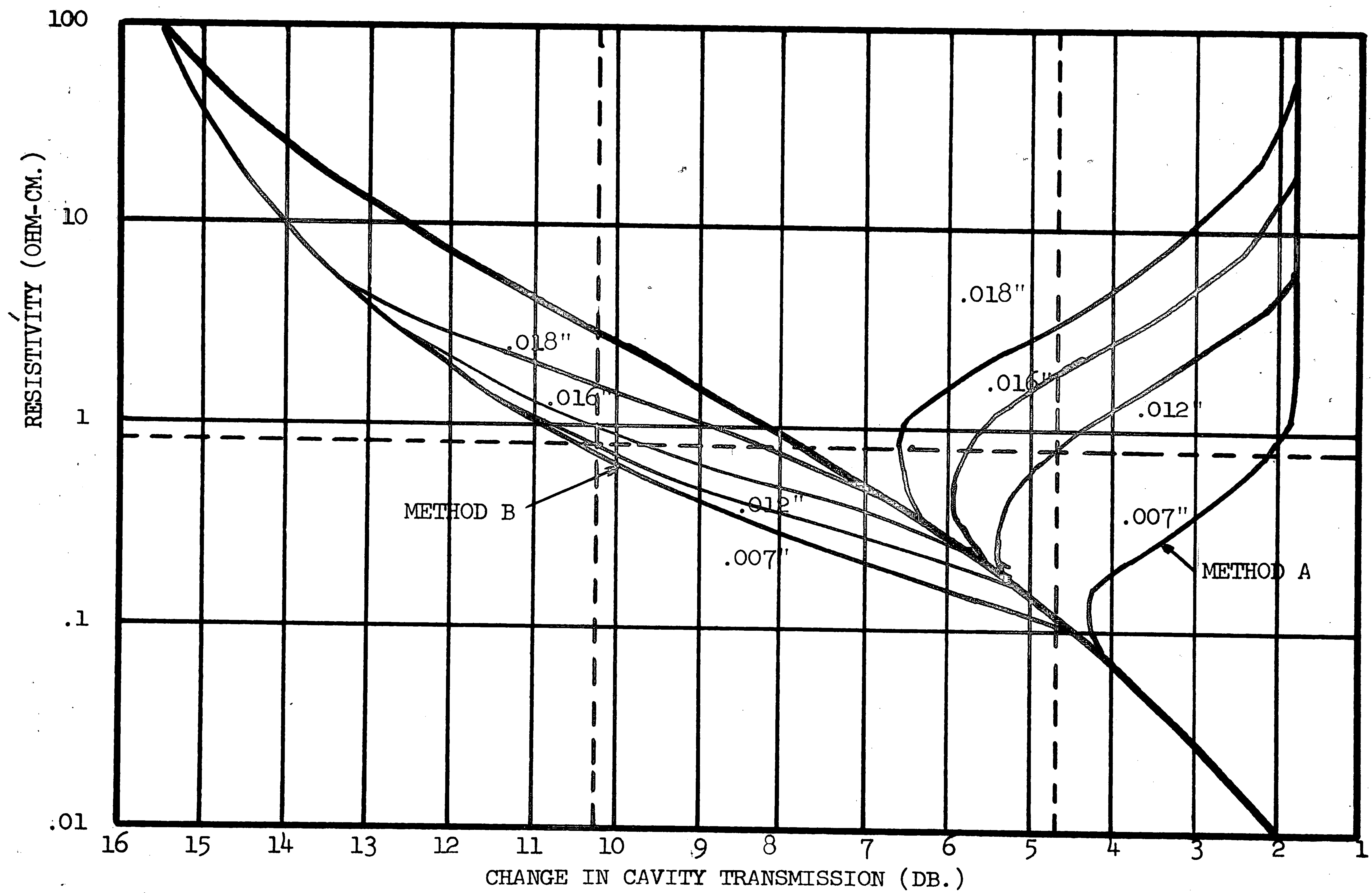


FIG. 12

CAVITY LOSS VS. RESISTIVITY AT 9Gc. (3)

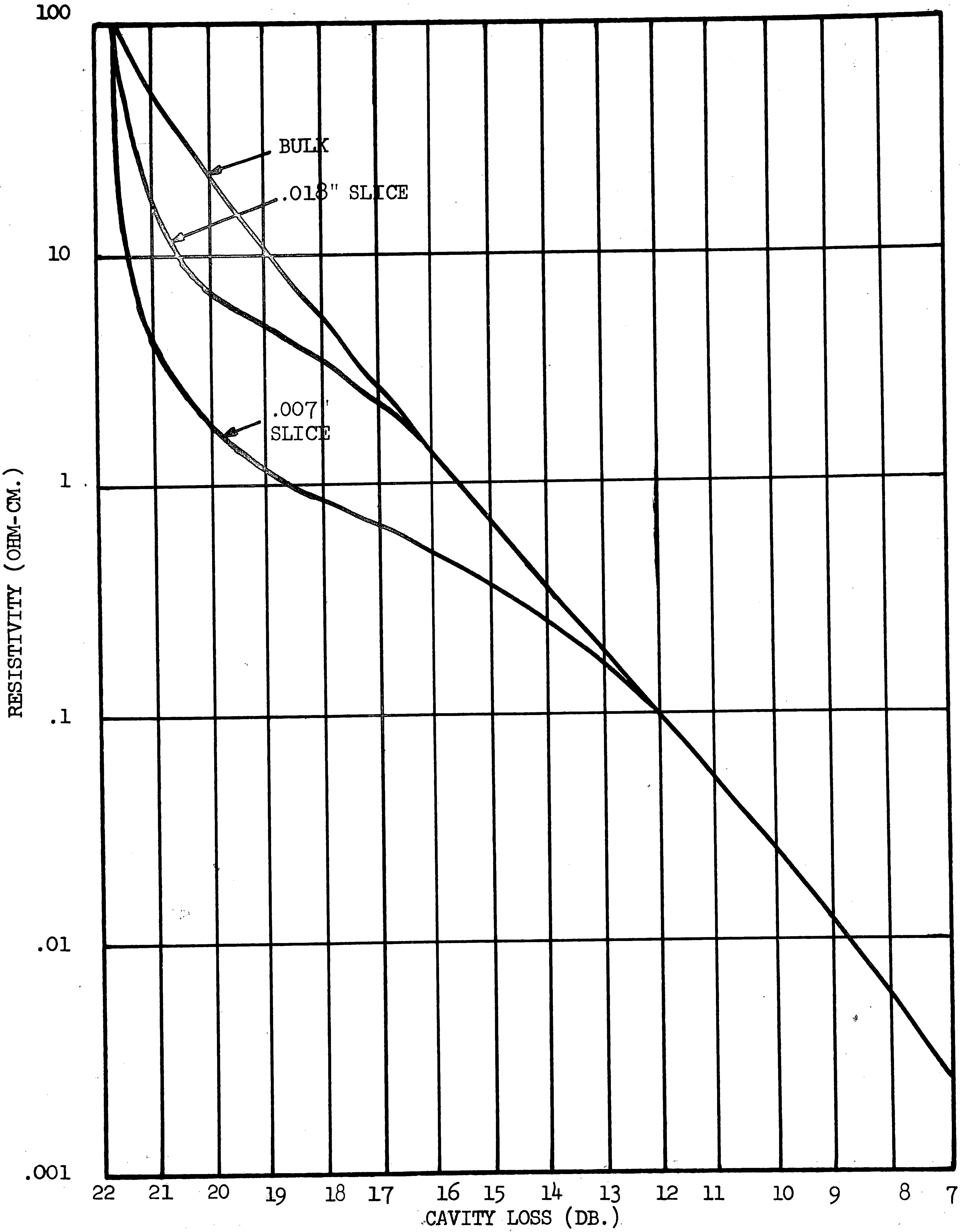


FIG. 13

CAVITY LOSS VS. RESISTIVITY AT 22Gc.

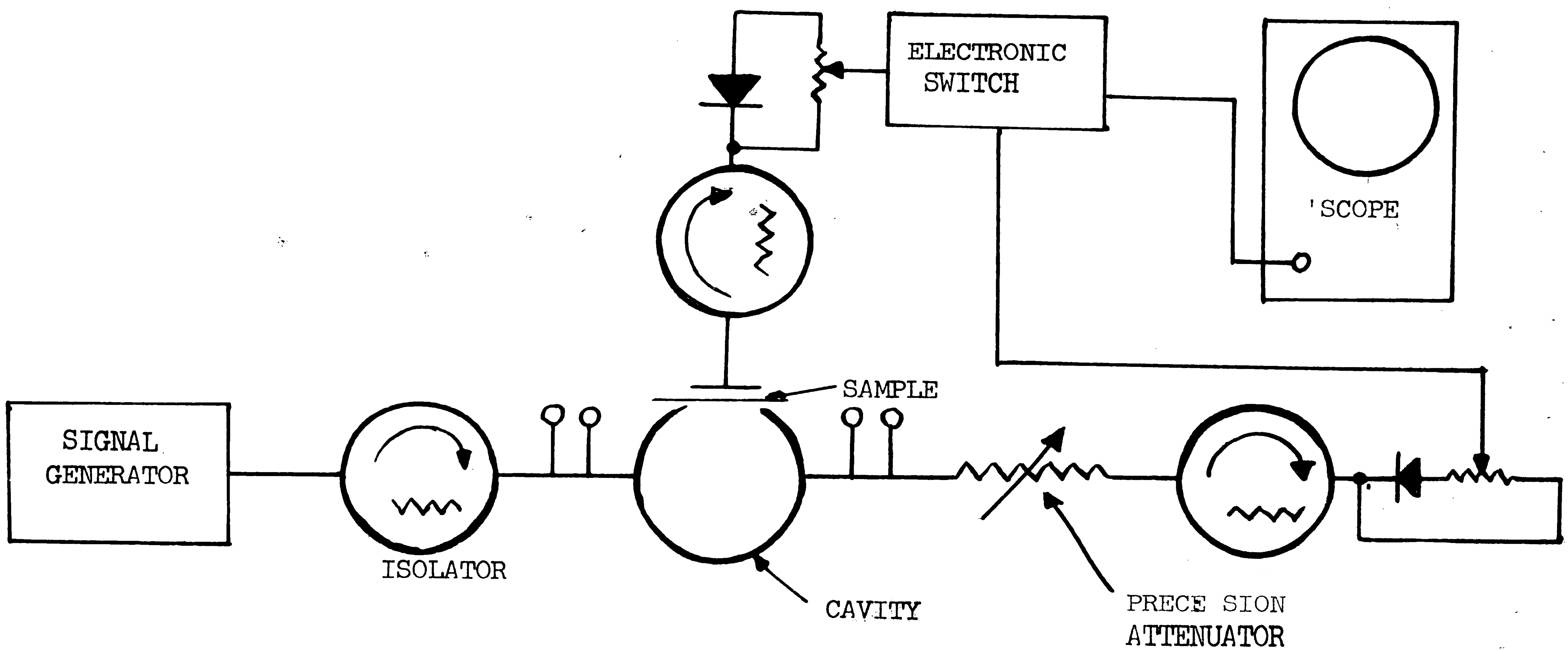


FIG. 14

TRANSMISSION LOSS CIRCUIT DIAGRAM (1)

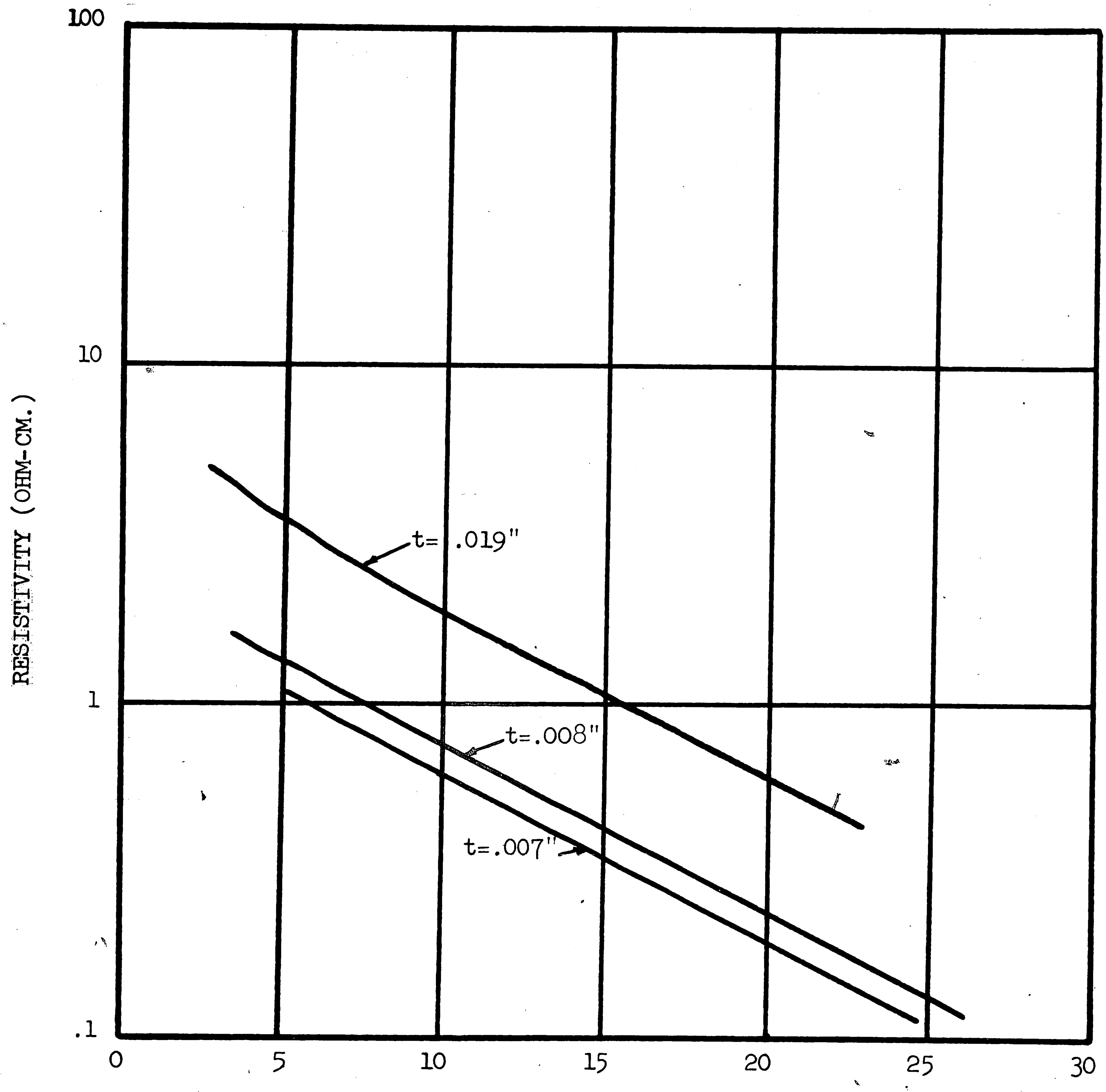


FIG. 15

TRANSMISSION LOSS VS. RESISTIVITY (1)

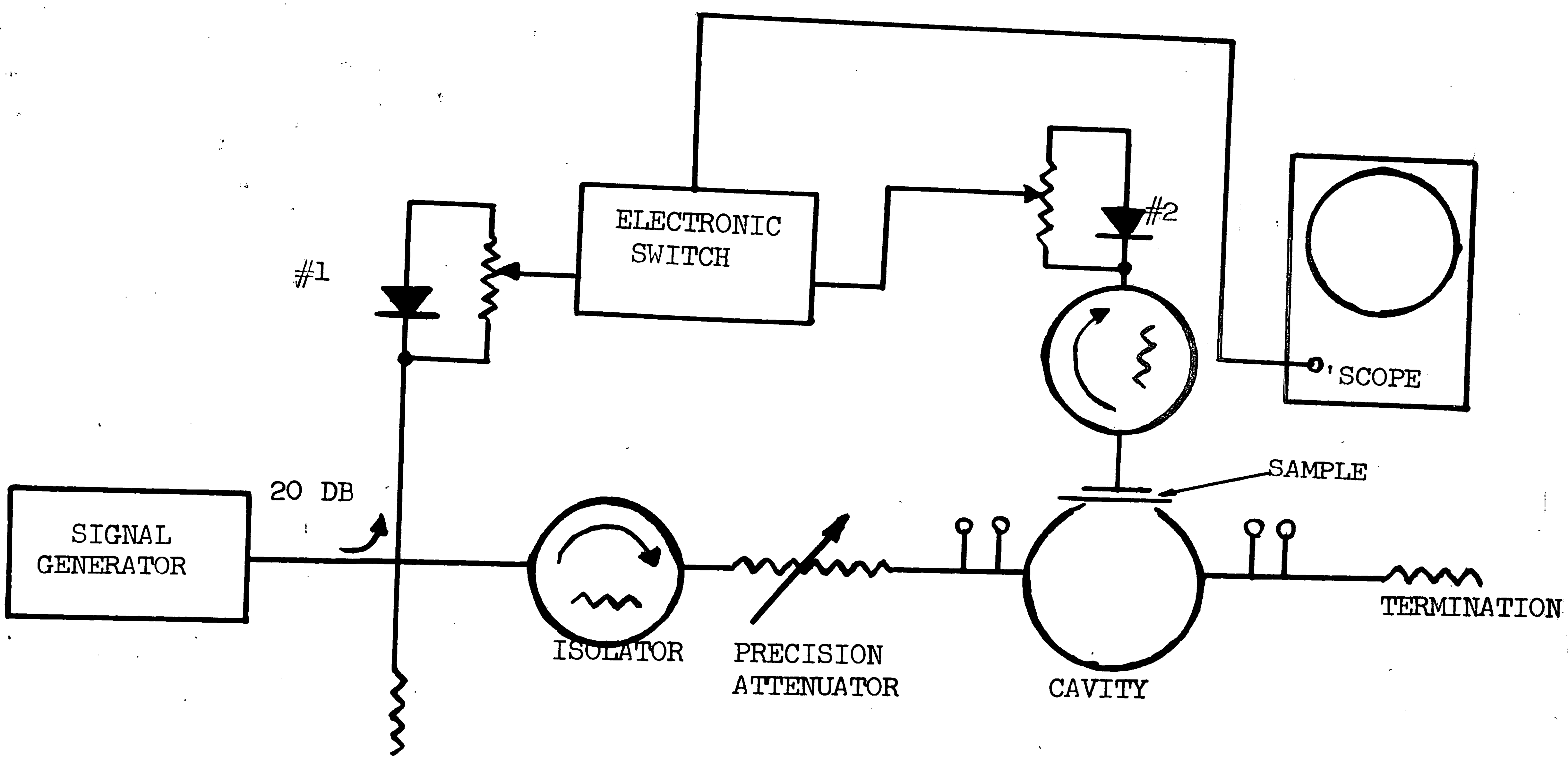


FIG. 16

TRANSMISSION LOSS CIRCUIT DIAGRAM (2)

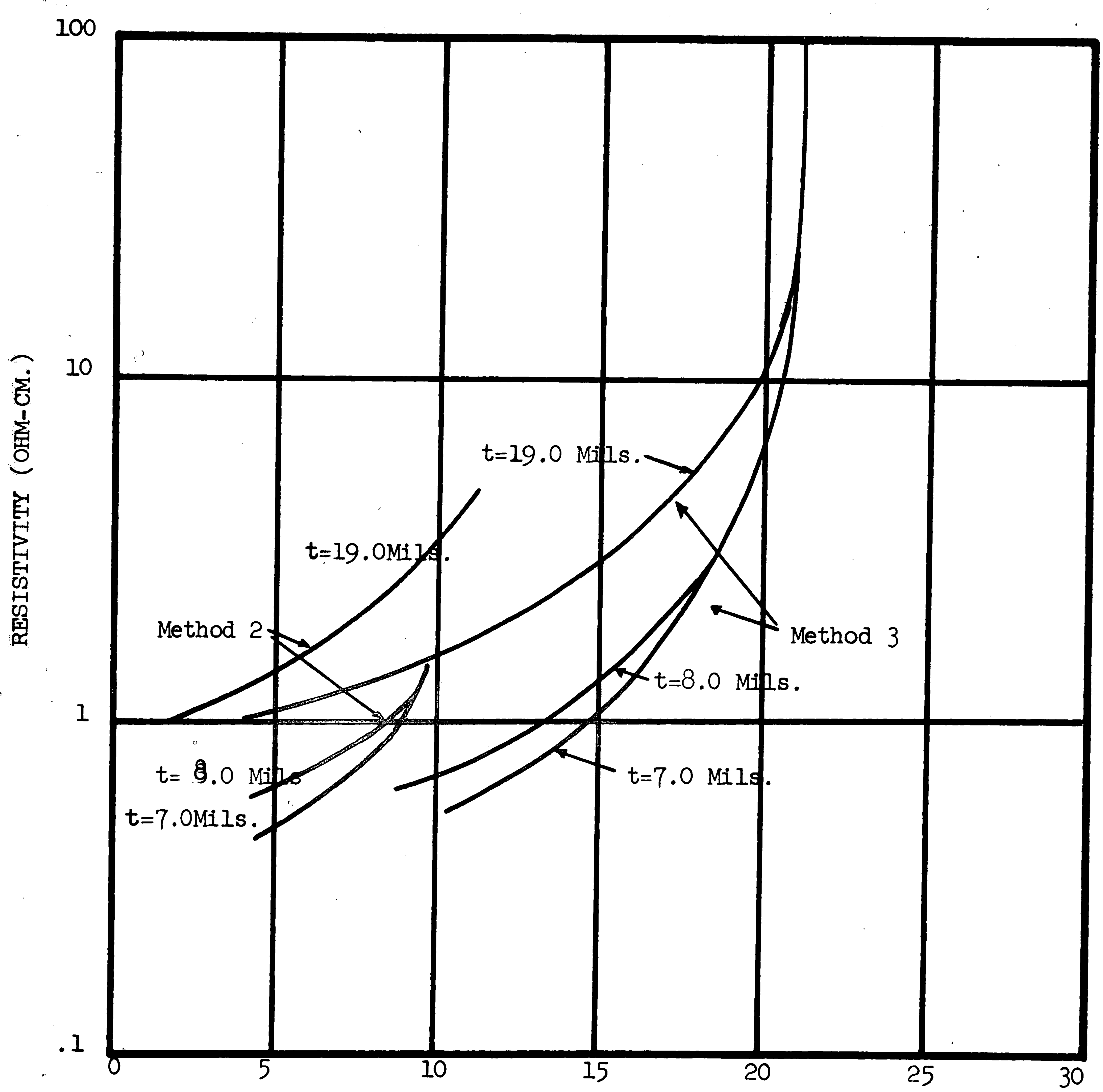


FIG. 17

TRANSMISSION LOSS VS. RESISTIVITY (2 & 3)

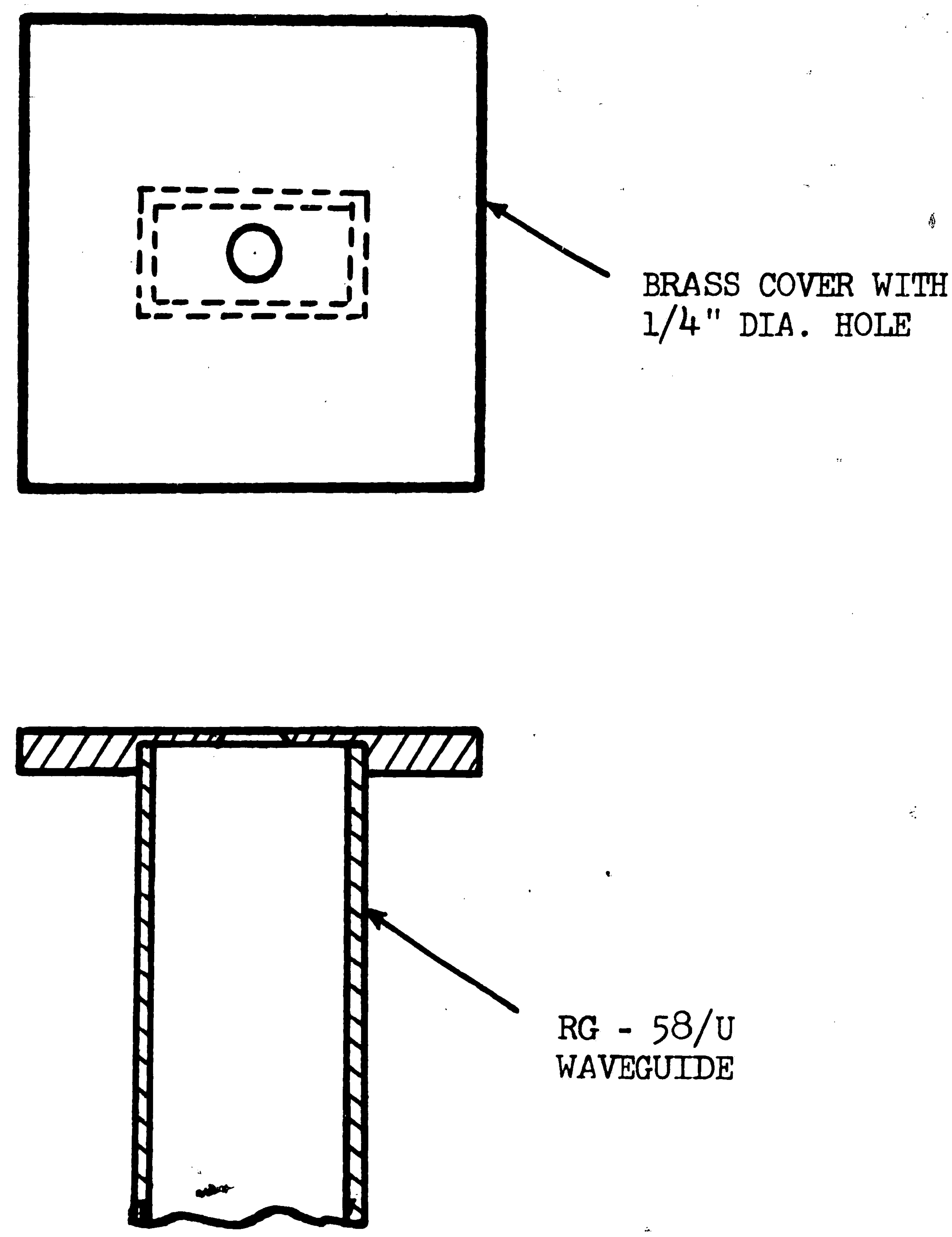


FIG. 18

TRANSMISSION LOSS FIXTURE

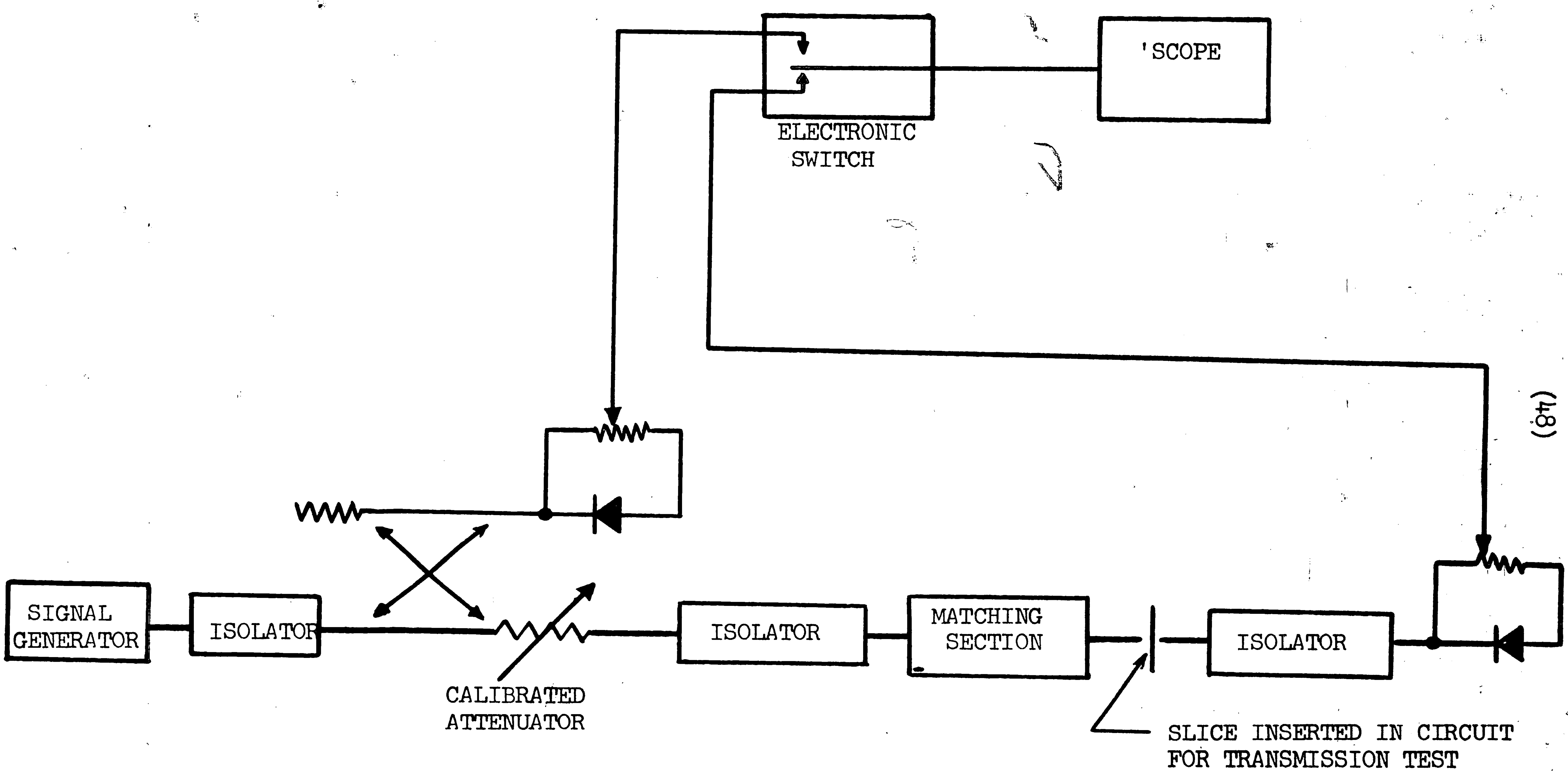


FIG. 19

TRANSMISSION LOSS CIRCUIT DIAGRAM (3)

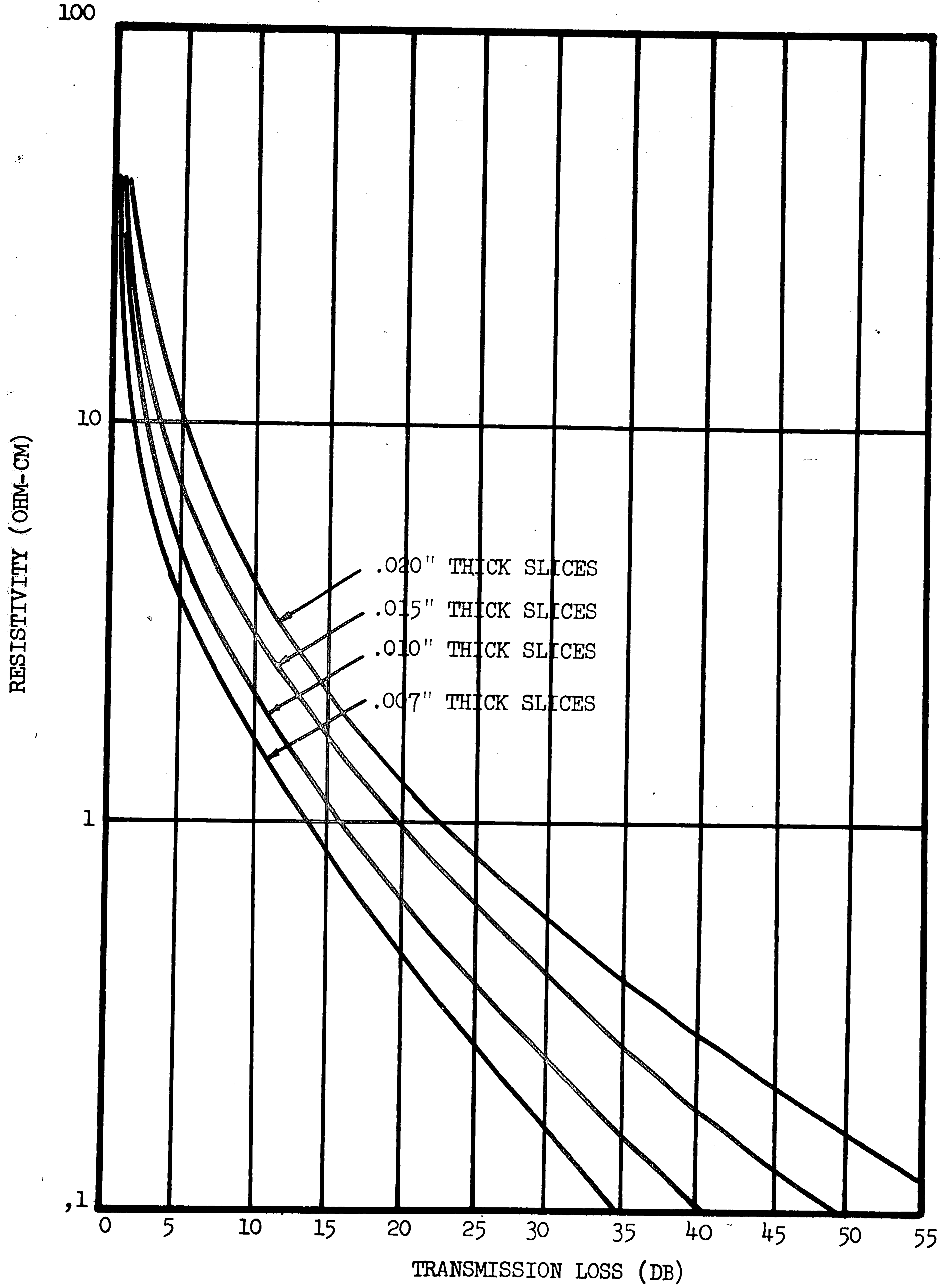


FIG. 20

TRANSMISSION LOSS VS. RESISTIVITY (3) AT 22Gc.

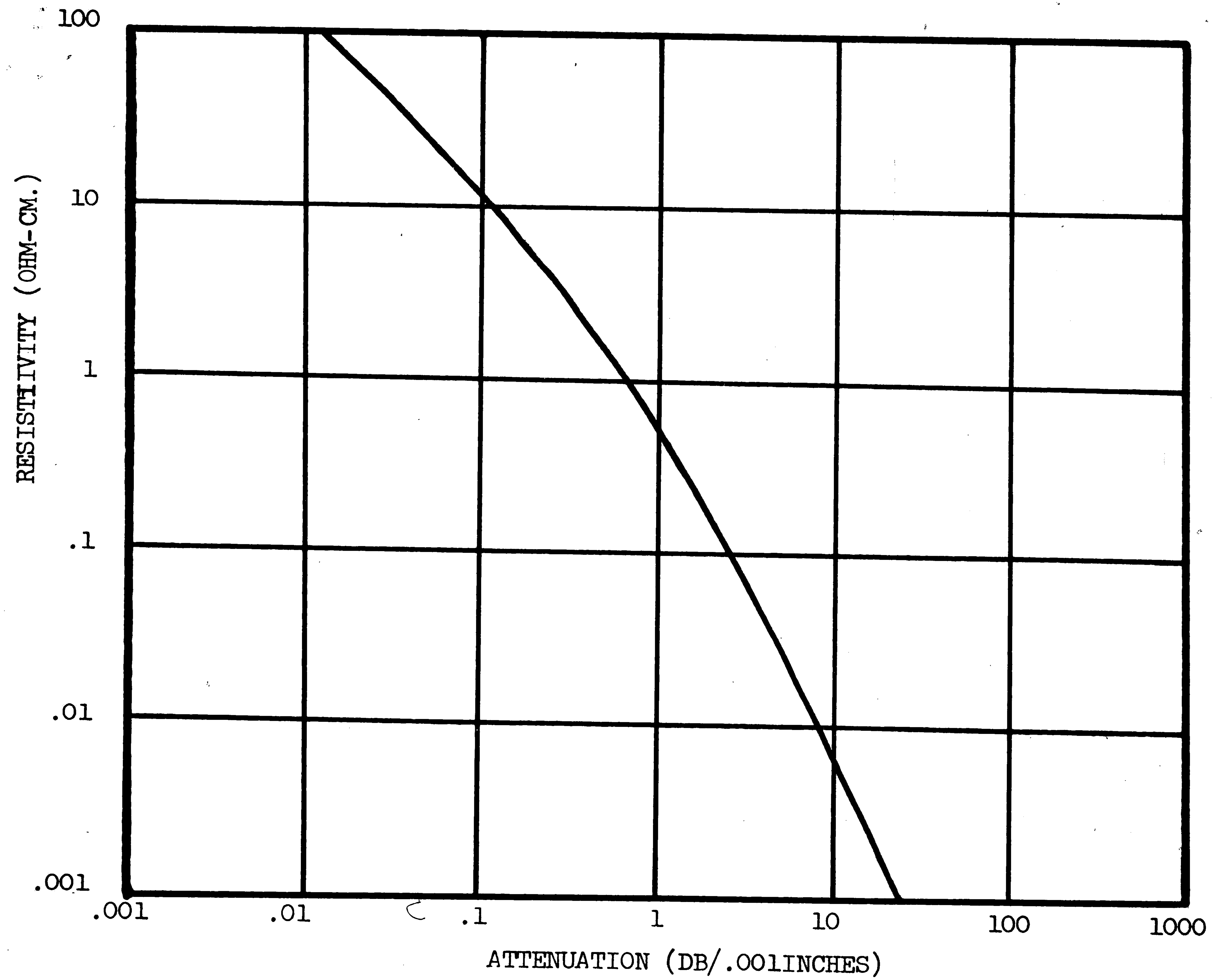


FIG. 21

RESISTIVITY VS. ATTENUATION/.001"

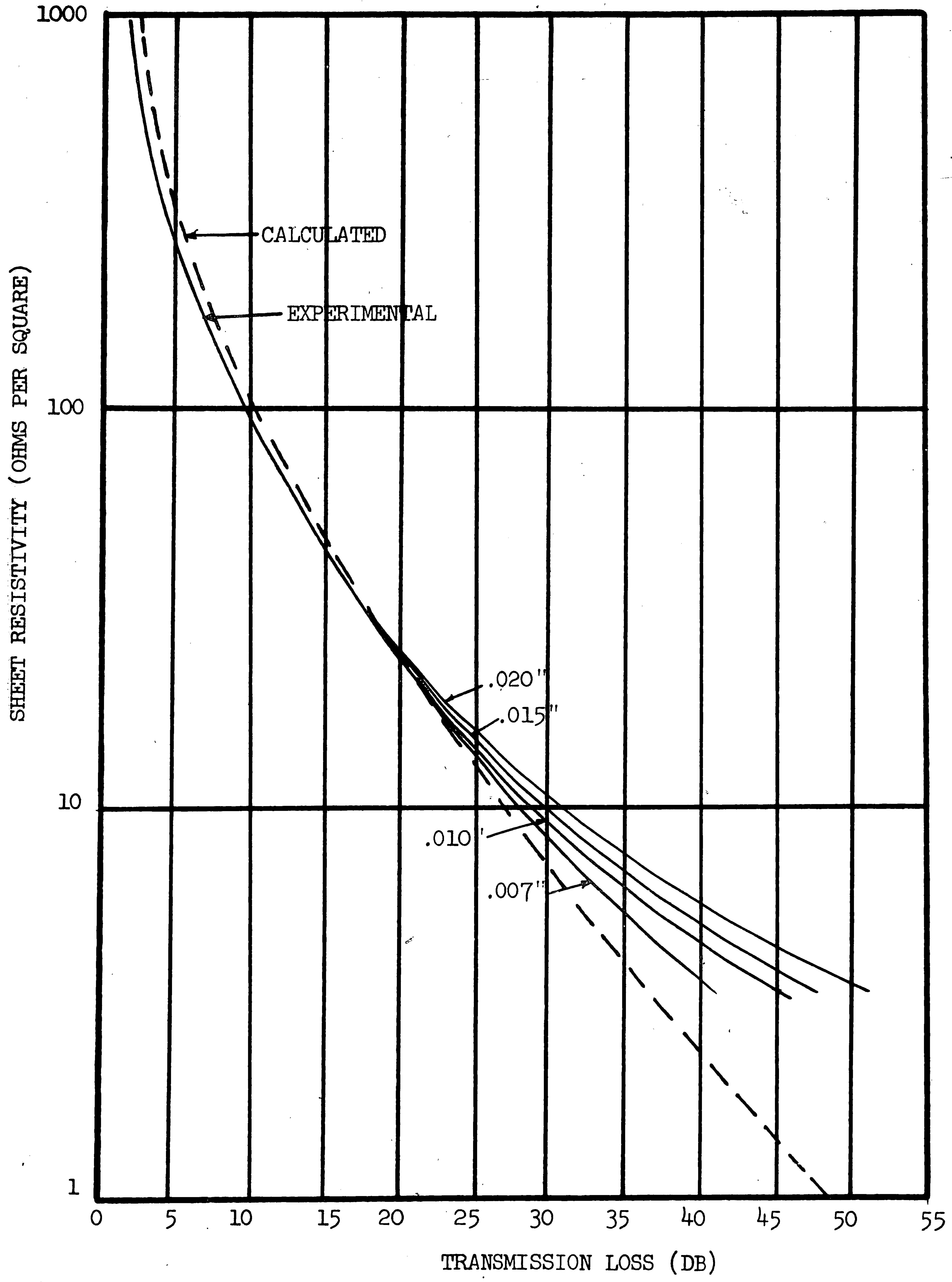


FIG. 22

SHEET RESISTIVITY VS. TRANSMISSION LOSS

VITA

Mr. James Roger Seifert was born on December 11, 1935 in Bethlehem, Pa. He attended public schools in Bethlehem through high school. Attending Lehigh University on a scholarship, he majored in Electrical Engineering and was elected a member of Eta Kappa Nu, the electrical engineering fraternity. He received a Bachelor of Science Degree in June 1957.

Mr. Seifert is presently employed by Western Electric Co. as a Test Planning and Design Engineer, responsible for the development and design of testing equipment for microwave devices. He was affiliated with Sylvania Microwave Tube Laboratory before joining Western Electric.